

RESEARCH ON ACTIVATED SLUDGE SETTLING BEHAVIOUR BASED ON SHORT-TERM TEMPERATURE VARIATIONS

by

**WH Rössle, W van der Merwe, A Chapman
LS Chueu & WA Pretorius**

Erwat Chair in Wastewater Management
Department of Chemical Engineering
University of Pretoria

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EXECUTIVE SUMMARY

Settling properties of activated sludge or mixed liquor suspended solids (MLSS) have been studied for more than 75 years at wastewater treatment plants. Temperature, together with MLSS concentration, has been acknowledged as important contributors to MLSS settling variations. These settling variations can be detected over short-term, from minutes up to diurnal periods, or over long-term, from weeks up to annual periods based on seasonal meteorological changes. Batch MLSS settling tests are performed on a regular basis at most treatment plants. The majority of these short-term MLSS settling test reports reflect the complete absence of any form of temperature compensation or even MLSS sample temperature (T_s) recordings.

This research project evaluates the effects of short-term temperature variations on MLSS settling parameters. The extent of typical plant temperature variations is demonstrated by short- and long-term reactor temperature (T_r) observations. Traditional batch MLSS settling tests are subsequently performed over such operational temperature ranges to quantify the variation in MLSS settling behaviour. The experimental work concludes with the implementation of an on-line MLSS settling test procedure at pilot- and full-scale reactors to develop settling models based on diurnal T_r fluctuations. These settling models demonstrate that parameter correlations improve when T_r is included in on-line MLSS concentration-based settling models.

Plant temperature recordings show significant short- to long-term variations. Local ambient temperature (T_a) and T_r fluctuate by about 20°C and 1.8°C respectively per day, and T_r changes by about 4°C within a week, as measured on-line at local plants during the test period in winter and spring. The method of aeration can have a significant impact on T_r . The difference in T_r of adjacent surface and bubble aeration reactors in the same plant was about 5°C, as T_r increases due to the warm air from blowers supplied to aeration diffusers. Large enough T_r and T_a variations exist at these local plants to affect MLSS settling test results.

The MLSS settling test cylinder environment and meteorological conditions have a direct influence on T_s during batch settling tests. Direct solar radiation increases the average T_s by 4.3°C, or by 0.15°C per minute, during a 30 minute MLSS settling test duration. This T_s

change leads to a sludge volume index (SVI) change of 63 mL/g, at an average SVI decrease of 14.8 mL/g per 1°C T_s increase. Changes to other parameters include an initial settling velocity (ISV) increase of about 0.12 m/hr for every 1°C T_s increase, together with a clarified supernatant turbidity increase of about 1.4 formazine nephelometric unit (FNU) for every 1°C T_s increase. T_s adjusts towards T_a before and during a batch MLSS settling test, thereby influencing MLSS settling results. Compensation for T_s variations during routine MLSS settling tests is nevertheless not reported as a common practice. To some extent, this is due to a lack of temperature-controlled MLSS settling test equipment.

An automated MLSS settling meter demonstrates a semi-continuous on-line method to determine settling parameters *in situ* at the operational T_r of a pilot- and full-scale plant. A basic polynomial fits 11 MLSS settling parameters that indicate in most instances improved MLSS settling at increased T_r . For the full-scale plant conditions, the average SVI decreases by 14.8 mL/g for every 1°C T_r increase. Similarly, for every 1°C T_r increase, the maximum settling velocity (u_{max}) increase is 0.1 m/hr, and time to reach maximum settling velocity (t_{umax}) decreases by 2.4 minutes. The incremental 5-minute duration average settling velocities increase over the first 15 minutes of a MLSS settling test, as the MLSS concentration decreases and the T_r increases. This direct incremental settling velocity trend with T_r is reversed between 15 and 30 minutes, as the average 5-minute MLSS settling velocity increases at a reduced T_r .

The inclusion of T_r in MLSS concentration-based settling best-fit correlations with SVI, u_{max} , and t_{umax} improves the coefficient of multiple determinations (R^2) by an average of 0.32 for full-scale plant conditions. Best-fit SVI models with u_{max} and t_{umax} have R^2 -values of 0.90 and 0.95 respectively. The developed models are only valid for the individual reactor MLSS conditions within the experimental parameter ranges.

The original Water Research Commission (WRC) research proposal (nr. 1274 of 2001) contained three research products:

1. Augmentation of mathematical process and clarifier models to incorporate floc conditions,
2. A pilot plant to simulate secondary wastewater treatment processes, and
3. Process control methodologies to generate floc with optimal settling properties to enhance final clarification.

The three research products were delivered as follows in this report:

1. Temperature was introduced and modelled as a variable in MLSS settling correlations,
2. A three-stage biological nutrient removal (BNR) pilot plant was commissioned to simulate typical activated sludge operation over an extended temperature range, and
3. Batch test methodologies to measure MLSS settling were determined with regards to reactor sample position, sample handling equipment and sample temperature. An on-line MLSS settling meter was developed and commissioned to reduce the inherent disadvantages of temperature changes occurring during batch MLSS settling test conditions.

The developed research products resulted in the following recommendations:

1. Sample or reactor temperature should be included in BNR and MLSS settling models, to ensure design and operational process control simulations are representative of plant conditions.
2. The successful pilot plant-scale operation, with a continuous raw sewage feed to simulate full-scale operational conditions, presents many challenges. The advantages related to the operational flexibility of a pilot plant provide sufficient reasons for future use of such plants for research and development work.
3. Temperature compensation and recording is necessary for batch MLSS settling tests. On-line settling monitoring removes most of the variable temperature conditions experienced during sample handling and testing in manual batch MLSS settling tests.

The main contribution of this project is to present temperature-based MLSS settling models, based on on-line pilot and full-scale plant studies. These models illustrate that an automated on-line MLSS settling meter is suitable to identify and model temperature related MLSS settling data with minimal experimental effort. The on-line MLSS settling detection method eliminates inherent temperature-based variations resulting from traditional batch MLSS settling tests.

Keywords: activated sludge, batch test, biofloc, clarifier, MLSS, model, settling, SVI, temperature, wastewater.

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NOMENCLATURE

Symbol or Acronym	Definition
a, b, c, d, e, f, g, h, i, j, k	regression coefficients
a, b, c	three periods of settling process
a, b, c	plant reactors used in experimental work
A, B, C, D, E	five settling stages of MLSS setting profile
Ave.	average
BNR	biological nutrient removal
C	Carbon
°C	degree(s) Celsius
CaCO ₃	calcium carbonate
Cl ₂	chlorine
cm	centimetre
COD	chemical oxygen demand
d	day(s)
DO	dissolved oxygen
DSVI	diluted sludge volume index
e.g.	for example
ERWAT	East Rand Water Care Company
<i>et al.</i>	and others
exp, e	exponent
ECP	exocellular polymers
EPBNR	excess phosphorus biological nutrient removal
f	function
FOG	fats, oils and grease
FNU	formazine nephelometric unit
g	gram(s)
g	gravitational acceleration constant
G	solids flux
g/ℓ	gram per litre
gSS/ℓ	gram suspended solids per litre
g/mℓ	gram per millilitre
h	settling meter liquid to MLSS interface height
hr	hour(s)

HRT	hydraulic retention time
i, ii, iii, iv	4 methods to acquire G
<i>in situ</i>	in natural or original place
ISV	initial settling velocity
kg	kilogram(s)
kHz	kiloHertz
kg/m ³	kilogram per cubic metre
ℓ	litres
LCVFA	long chain volatile fatty acid
m	metre(s)
mm	millimetre
mA	milliAmpere
mg	milligram(s)
mg/ℓ	milligram per litre
mgN/ℓ	milligram nitrogen per litre
mgSS/ℓ	milligram suspended solids per litre
meq/gSS	milliequivalent per g suspended solids
mMol	milliMole concentration
m/hr	metre per hour
min.	minute(s)
mℓ	millilitres
mℓ/g	millilitres per gram
mℓ/ℓ	millilitres per litre
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
mV	millivolt
n	number of observations
n	constant in empirical Vesilind equation
N	nitrogen
N/A	not available / applicable
NDBEPR	nitrification-denitrification biological-excess-phosphorus removal
NH ₄ ⁺	ammonium
NO ₃ ⁻	nitrate

NO_2^-	nitrite
Ns/m^2	Newton seconds per square metre
$o\text{-PO}_4$	ortho-phosphate
P	phosphorus
pH	logarithmic scale of activity of hydrogen ion
PLC	program logic controller
p value	probability value
R^2	coefficient of multiple determinations
RAS	return activated sludge
RBCOD	readily biodegradable COD
rpm	revolutions per minute
s	second
S	sulphide
SBR	sequencing batch reactor
SBCOD	slowly biodegradable chemical oxygen demand
SG	specific gravity
SRT	sludge retention time
SS	suspended solids
SSVI	stirred specific volume index
$\text{SSVI}_{3.5}$	stirred specific volume index at 3.5 g/ℓ
St. dev.	standard deviation
SV_{30}	30 minute settled sludge volume
SVI	sludge volume index
$\text{SVI}_{3.5}$	SVI at 3.5 g/ℓ
T	temperature
T_a, T_a	ambient temperature (atmospheric)
T_s, T_s	sample temperature
T_r, T_r	reactor temperature
$T_{\text{raw}}, T_{\text{raw}}$	raw sewage (wastewater) temperature
T_0, T_5, T_{15}, T_{30}	temperature after 0, 5, 15, and 30 minutes
t	time
TDS	total dissolved solids
Temp	temperature

Tur	supernatant turbidity
t _{umax}	time to reach u _{max}
t-ratio	ratio of estimated parameter value to estimated parameter standard error
u	discrete biofloc settling velocity
u ₁ , u ₂ , u ₃ , u ₄ , u ₅ , u ₆	incremental 5-minute settling velocities
u _{max}	maximum (constant) 1-minute settling velocity
u _{ave}	average 30-minute settling velocity
UP	University of Pretoria
V	volt
v _o	constant in empirical Vesilind equation
vs.	versus
V _s	ZSV in empirical Vesilind equation
VFA	volatile fatty acid
WCW	water care works
WRC	Water Research Commission
X	MLSS concentration
x	independent regression variables
x, x ₁ , x ₂	horizontal axes coordinates in 2- and 3-D graphs
y	dependent regression variables
y, y ₁ , y ₂	vertical axes coordinates in 2- and 3-D graphs
ZSV	zone settling velocity
ε	random error
μm	micrometre(s) [10 ⁻⁶ m]
σ ²	error variance
1, 2	experimental plants
1, 2, 3, 4	four stages in MLSS settling profile
1, 2, 3, 4	successive sections in aerobic zone
2-D	2 dimensional graphs or correlations
3-D	3 dimensional graphs or correlations
I, II, III, IV	four classes of MLSS settling
<, <=, =, >	smaller, smaller or equal, equal, larger
/, .	divide, multiply
%	percentage

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1 INTRODUCTION

This chapter introduces the concept of temperature dependent MLSS settling tests, and it highlights the lack of temperature compensation or recording in these tests. The experimental focus was established on aspects of MLSS settling, according to the objectives of the project.

1.1 Background

This report is the result of a project proposal approved by the Water Research Commission (WRC) and registered as project K5/1340 in May 2002: “*Biofloc modifications for sludge settleability improvements from selected BNR process conditions and configurations; pilot and full-scale based settling behaviour evaluations for final clarification enhancement*”. The project work was conducted from 2002 to 2007 at the East Rand Water Care Company (ERWAT) Olifantsfontein Water Care Works (WCW), in liaison with the ERWAT Chair in Wastewater Management, situated at the University of Pretoria (UP).

The initial experimental work focussed on investigations into the settleability characteristics of activated sludge generated by a pilot plant, as measured by conventional batch settling tests. At the same time, an on-line automated activated sludge settling meter was developed by ERWAT. From the on-line settleability data, it soon became apparent that the reactor and ambient temperature significantly influenced settleability behaviour. The pronounced diurnal temperature fluctuations at the pilot plant produced temperature dependant settling profiles that were modelled accordingly with commercial software. The pilot plant settleability evaluation was repeated at a full-scale biological nutrient removal (BNR) reactor to confirm and model short-term settleability variations under typical operational plant conditions.

1.2 MLSS settling behaviour

BNR processes suffer at times from activated sludge or mixed liquor suspended solids (MLSS) settleability problems (Grady and Filipe, 2000) that disturb the BNR treatment efficiency. Short-term (diurnal) temperature variations in reactor temperature (T_r) have been observed as having an effect on MLSS settleability (Wilén *et al.*, 2006). Scherfig *et al.* (1996) showed that T_r fluctuations are very dependent on local meteorological factors, such as ambient temperature (T_a), wind, and cloud cover. Where MLSS settling properties are

traditionally determined batch-wise in 1 litre (ℓ) size cylinders (Gernaey *et al.*, 1998), it is to be expected that unless special care is taken, these meteorological factors will have an effect on the sample temperature (T_s). T_s is usually not reported in batch MLSS settling evaluations that is used to represent BNR MLSS settleability (Ekama *et al.*, 1997).

Based on the temperature dependency of MLSS settling, three aspects of settling evaluations are relevant to this project. These aspects are:

1. the T_r and T_a variations in operational plants,
2. batch MLSS settling tests under typical test conditions, and
3. on-line MLSS settling monitoring at pilot- and full-scale plant reactors.

On-line MLSS settling monitoring data contains semi-continuous MLSS settling profiles (Vanrolleghem *et al.*, 1996). These type of settling profiles form the basis for the temperature dependent MLSS settling models proposed in this project. Settling parameter predictions are subsequently possible with these T_r -based models. These settling models assist with site-specific BNR MLSS settleability management.

1.3 Experimental work

The experimental work consists of two main stages, which is an equipment construction stage and an experimental MLSS settleability test stage. The pilot plant construction and commissioning is followed by the completion of an on-line settling meter development. The construction and commissioning of the experimental equipment caused a delay in the completion of the scheduled experimental work.

The experimental MLSS settleability work report is divided in three distinct phases according to the project scope. The first phase is based on temperature observations at different plant reactors to determine the extent of typical T_r and T_a variations. The second phase includes batch MLSS settling tests to determine settling parameter changes occurring during operational temperature variations. The final experimental phase, at pilot and full-scale plants, consists of on-line MLSS settling evaluations with the automated MLSS settling meter. This stage concludes with statistical calculations to compare the temperature-based MLSS settling models obtained from the on-line settling profiles.

1.4 Project scope

The final aim of this project is to determine the effects of short-term temperature variations on MLSS settling parameters. The following five sections address the project scope:

- Literature review on the influence of temperature on MLSS settling (Chapter 2):

The review covers the principles and monitoring of MLSS settling, operational plant temperature conditions, as well as batch and on-line MLSS settling tests changes related to temperature variations. The aim of the review is to identify temperature effects reported during MLSS settling, as well as techniques or models that are in use to compensate for temperature variations.

- Temperature survey at plant reactors (Chapter 3):

The extent of temperature (raw sewage, reactor, ambient) fluctuations is established at different plant reactors over short- and long-term periods.

- Batch MLSS settling evaluation based on temperature variations (Chapter 4):

Changes in batch MLSS settling parameters are evaluated according to container size, reactor zone sample source, as well as operational container environment, based on temperature variations.

- On-line MLSS settling evaluation based on diurnal temperature variations (Chapter 5):

Diurnal changes in on-line MLSS settling meter data is established, before best-fit models of settling parameters illustrate the impact of T_r inclusion in MLSS concentration-based models. Sludge volume index (SVI) relationships are correlated with the maximum settling velocity (u_{max}) and the time (t) to reach u_{max} (t_{umax}). Finally, simulations of 11 settling parameters with MLSS concentration and T_r in simplified models illustrate the extent of settling parameter changes occurring during a temperature variation.

- Pilot plant commissioning and on-line MLSS settling evaluation based on diurnal temperature variations (Appendix A):

The pilot plant construction and operational performance details are supplied in Appendix A. This section also includes an on-line MLSS settling evaluation, on which the full-scale plant MLSS settling evaluation was based.

1.5 Conclusions

The purpose of this project is to demonstrate that temperature variations are an essential component of traditional MLSS settling determinations. Three temperature-related MLSS settling aspects in this project comprise of short- and long-term plant temperature fluctuation identification, batch MLSS settling evaluations, and on-line MLSS settleability monitoring. The development of MLSS settling models and parameter correlations that incorporate temperature concludes the project.

This development of plant specific temperature dependent MLSS settling correlations provides the opportunity to improve the traditional MLSS concentration-based settling models. Specialised methods and equipment are required to capture the effects of operational plant temperature variations. Improved MLSS settling models, based on these temperature variations, will provide additional information to assist with the management and design of wastewater treatment plants.

2 LITERATURE REVIEW

This chapter reviews basic MLSS settling tests, operational temperature data, as well as batch and automated MLSS settling tests and parameters, which was applied in the experimental project stage. The purpose of this review is to identify reported correlations, or lack thereof, between MLSS settling parameters and temperature.

2.1 Background

MLSS settling has been investigated for more than 75 years in the wastewater industry (Dick and Vesilind, 1969), during which time numerous reports confirm that temperature influences aspects of MLSS settleability. Werker (2006) classifies dynamic temperature conditions as a dominant environmental factor in wastewater treatment plant processes. These temperature variations are characterised by short-term (diurnal) and long-term (seasonal) cyclic fluctuations (Baetens *et al.*, 1999) that are present at plant reactors. Makinia *et al.* (2005) modelled these fluctuations as basic sinusoidal trends, which follow both cyclic daytime to nighttime and summer to winter heating and cooling stages. These temperature fluctuations lead to physical, chemical, and biological changes in MLSS (Janssen *et al.*, 2002) that will influence the settleability of the MLSS.

Ekama *et al.* (1997) consider the indirect effects of temperature fluctuations on MLSS settleability, such as structural changes in biofloc, as more important than direct effects, such as liquid viscosity and density changes. The combined direct and indirect temperature fluctuation effects on MLSS settleability have not been studied in any detail (Krishna and Van Loosdrecht, 1999). Long-term temperature effects on MLSS settling are well described, as seasonal BNR process performance variations and related MLSS settleability changes can be easily detected from long-term trends (Osborn *et al.*, 1986).

Information and implementation guidelines for temperature compensation, based on short-term temperature variations during MLSS settling tests, are still lacking (Wilén, 1999). The effects of these temperature variations during basic MLSS settling tests, as represented by empirical settling correlations, need to be quantified and modelled accordingly.

This literature review considers the effects of short-term temperature variations on MLSS settling parameters. The review focuses on four aspects of MLSS settling tests, which are in accordance with the objectives of this project:

1. principles and monitoring of MLSS settling,
2. operational plant temperature conditions,
3. batch MLSS settling tests and temperature variations, and
4. on-line MLSS settling tests and temperature variations.

2.2 Principles and monitoring of MLSS settling

2.2.1 MLSS settling and temperature relationship

The basic ecological unit of MLSS is a biofloc (Bux and Kasan, 1994a). Inside such a biofloc, temperature variations result in physiochemical and microbiological changes (Makinia *et al.*, 2005). Gerardi (2002) recognizes that these physical and biological changes have opposite effects on biofloc settling.

On the one hand, the physical effects of a temperature increase leads to improved (faster) biofloc settling, due to lower water viscosity and density, as well as structural biofloc changes. On the other hand, bacterial activity increases at a higher temperature. Bioflocs absorb or entrap the increased production and accumulation of insoluble biological secretions, such as lipids and oils, and this leads to worse (slower) biofloc settling. Air or gas bubble entrapment, usually from denitrification of anaerobic sludge rich in nitrate (Kazami and Furumai, 2000), decreases this sludge settling velocity further.

These opposing and time-dependent temperature effects change biofloc characteristics (Örmeci and Vesilind, 2001). Temperature variations before and during settling tests complicates MLSS settling evaluations.

2.2.2 MLSS settling and MLSS concentration relationship

Throughout the MLSS settling process, the settling velocity of a particle or a singular biofloc depends on its individual characteristics, as well as interactions with other particles or bioflocs (Mazzolani *et al.*, 1998). Figure 2-1, adapted from Ekama (1988),

illustrates in this settling process the relationship between MLSS concentration and interparticle actions or flocculation tendency. MLSS settling and liquid clarification processes are divided into four classes according to the MLSS concentration and interparticle flocculation tendency.

The top sections of the graph (Classes I and II) represent liquid clarification. Single particles settle without interparticle action during Class I, and bioflocs settle with limited interactions during Class II, governed by the flocculation tendency. Hindered MLSS settling follows, represented in the middle section of the graph (Class III) to indicate the switch to zone settling at constant velocity. The bottom section of the graph (Class IV) represents the reduced settling velocity during transition, before the final compression or thickening leads to a stationary settled MLSS (Dupont and Dahl, 1995).

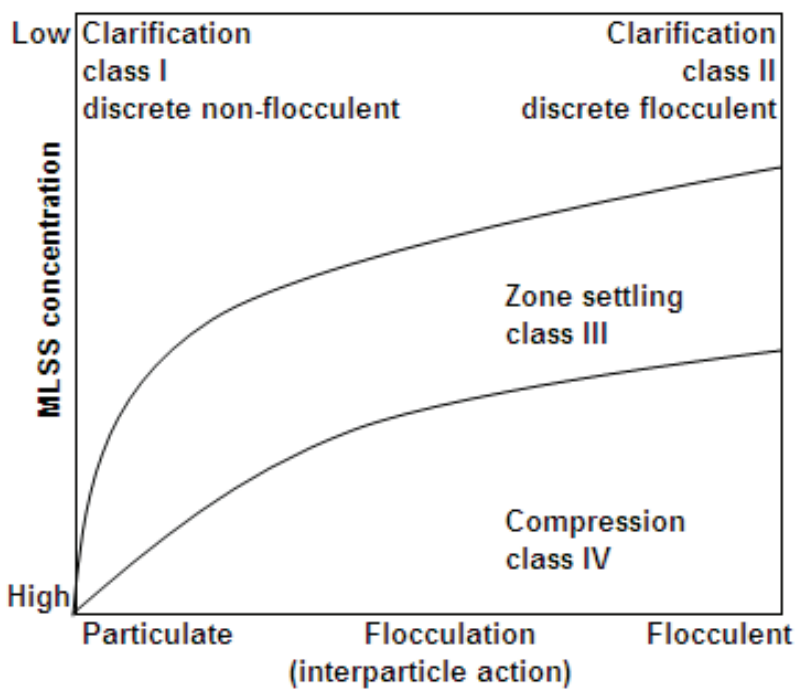


Figure 2-1 MLSS settling behaviour classified as Class I to IV according to MLSS concentration and interparticle actions

Basic mathematical equations illustrate the liquid clarification or Class I MLSS settling process, as well as the associated effects of temperature variations on settling. The resulting force of gravity and frictional shear (Catunda and Van Haandel, 1992) determines the settling velocity of individual particles. Due to the low MLSS

concentration of Class I settling, the particle motion is not affected by other particles, by the settling container wall, or by turbulent currents (Kolmetz *et al.*, 2003). This particle settling in water is temperature dependent according to fundamental correlations. Class I clarification can thus be modelled accurately from basic principles in theoretical models.

Class II to IV flocculent clarification to MLSS compression processes, at increasing MLSS concentration ranges, depend on complex forces in a matrix of interlinked bioflocs (Catunda and Van Haandel, 1992). Keller *et al.* (2002) concluded that these mechanisms of MLSS flocculation (Class II to IV) are still poorly understood. These mechanisms depend on interrelated physical, chemical, and biological factors (Jin *et al.*, 2003) that are all temperature dependent. Stypka (1998) and Biggs *et al.* (2003) confirmed that these processes couldn't be presented in a fundamental theoretical model without experimental settleability tests. Class II to IV processes are thus based on empirical settling models.

The four settling classes shown in Figure 2-1 indicate that MLSS settling is dependent on two factors, (i) the MLSS concentration, and (ii) the particle flocculation tendency. Several models have been developed for general and specific use to represent MLSS settleability (Krebs, 1995). According to the literature, the MLSS concentration is the only factor considered in most of these settling models.

2.2.3 MLSS settling parameters: identification and development

Ekama *et al.* (1985) define the MLSS settling profile as the basic measurement of a manual MLSS settling test. Settling parameters that are calculated from this profile include the settled MLSS volume after 30 minutes (SV_{30}), settling indexes such as the SVI, as well as settling velocities occurring during the different stages of the settling process. The magnitude of these settling parameters that represent a well-settling MLSS depends on local plant conditions and process performance requirements.

Cloete and Muyima (1997) specify that settling parameters of a well-settling MLSS represent a fast settling MLSS leaving a clear supernatant, combined with a stable settled MLSS at a reduced volume. The features of such a well-settling MLSS relate to the settling parameter guidelines according to four stages in the MLSS settling profile. These features are summarised in Table 2-1, as adapted from Tandoi *et al.* (2006), and Cloete and Muyima (1997).

Table 2-1 MLSS settleability criteria according to four settling stages

Settling parameter	MLSS criterion
Liquid clarification	SS concentration ≤ 15 mgSS/ ℓ
Flocculation (stage 1)	Commences after a few (2 to 5) min.
ZSV (stage 2)	Well-settling > 3 m/hr
	Light = 2 to 3 m/hr
	Bulking < 1.2 m/hr
Transition (stage 3); Compression (stage 4)	Thickened (not excessive volume), No guideline
Stability	No rising for few (2 to 3) hours
SVI	Well-settling < 100 to 150 mL/g
	Light = 100 to 200 mL/g
	Bulking > 150 to 200 mL/g

For a well-settling MLSS, the stage 1 reflocculation duration is about 2 to 5 minutes, followed by the stage 2 zone settling velocity (ZSV) proceeding at a constant velocity of more than 3 m/hr. There are no guidelines available for the stage 3 and 4 transition and compression stages, although the compressed MLSS volume should be concentrated to occupy a small volume. The stage 4 compressed MLSS should remain settled for a few hours, without rising or disintegrating. A clarified supernatant suspended solids (SS) concentration less than 15 mgSS/ ℓ indicates sufficient removal of SS from the clarified supernatant.

A SVI lower than about 100 to 150 mL/g indicates good MLSS settling, while a higher SVI indicates poor settling (Casey *et al.*, 1995). These high SVI conditions are usually, but not always, associated with a bulking MLSS (Blackbeard *et al.*, 1986). Bulking is a state where the MLSS settling velocity is low and the compression is poor (Novák *et al.*, 1993). Good MLSS settleability can be defined as a fast settling MLSS with a low SVI (Jenkins *et al.*, 1984).

Bye and Dold (1998) reviewed the basic settling parameters calculation methods used to obtain settleability data. Table 2-2 lists a summary of these techniques. Three basic calculation techniques between MLSS concentration and initial settling velocity (ISV) are established by (i) direct measurement, (ii) using existing correlations based on indexes

such as SVI, and (iii) using a clarifier operational chart, also based on indexes such as SVI (Hasselblad and Xu, 1996).

Table 2-2 MLSS settling parameters development techniques and use

Step	Action	Method
1	Determine MLSS concentration (X)	Standard Method 2540D (APHA, 1998) or MLSS concentration meter
2	Determine settling profile	Plot of settling volume or interface height vs. time for 30 minutes
3	Determine SV_{30}	Read from settling profile and calculate settled volume after 30 minutes
4	Determine ISV	Read from settling profile and calculate settling velocity between 2 and 5 minutes
5	Determine ZSV	Read from settling profile and calculate settling velocity at constant slope section
6	Calculate SVI	SV_{30} / X
7	Calculate solids flux (G)	$G = ZSV \cdot X$
8i	Generate flux curve directly from experimental data	G vs. X (8 to 12 MLSS samples with X range from 2 to 12 g/ℓ)
8ii	Generate flux curve from empirical equation (e.g. $V_s = v_o e^{-nX}$)	Fit ZSV and X by regression to v_o and n $V_s = v_o e^{-nX}$ with V_s and X data
8iii	Generate flux curve from correlations of SVI with v_o and n	$v_o = f(SVI)$, $n = f(SVI)$ $V_s = v_o e^{-nX}$ with V_s and X experimental data
8iv	Obtain G from operational chart	Read off flux by using SVI and X

Kazami and Furumai (2000) believe future MLSS settling research will be focussed to replace the flux curve experimental method (8i in Table 2-2), as the experimental procedure is based on time-consuming and laborious tests. Multiple batch settling tests at a range of MLSS concentrations (at least 8 tests from about 2 to 12 g/ℓ, Ekama *et al.*, 1985) are required in this step for a flux curve generation. The preferred method for regular use is to apply correlations to relate MLSS settling velocity to basic measurable settling parameters, such as SVI (8iii or 8iv in Table 2-2). Vanderhasselt and Vanrolleghem (2000) caution, however, against the indiscriminate use of such correlations, as the MLSS settling velocity is influenced by factors not normally incorporated in correlations between MLSS concentration and SVI.

2.2.4 MLSS settling indexes

2.2.4.1 SVI

Mohlman, as cited by Dick and Vesilind (1969), developed the SVI in 1934 to be a basic measure of the physical properties of MLSS. The SVI test is regarded in certain circumstances as an unreliable settling measurement, as the initial MLSS concentration influences the SVI inconsistently (Catunda and van Haandel, 1992). Ekama *et al.* (1985) found SVI comparison to be most unpredictable when the MLSS samples are sourced from different plants at different MLSS concentrations, while Berkay (1998) considered the SVI as unreliable when the MLSS settleability is poor. Poor settleability is usually found in bulking MLSS (Blackbeard *et al.*, 1986) or in settled MLSS with a high SV_{30} ($SV_{30} > 400 \text{ mL/L}$, Ekama *et al.*, 1985). Schuler and Jang (2007) summarised the criticism against SVI, by noting that the SVI is a composite, indirect measurement that may not be representative of the four settling classes taking place in a secondary settling tank.

These and other inadequacies of SVI are categorised in Table 2-3 as five features of the MLSS sample. The features in Table 2-3 indicate that SVI test results interpretation depends largely on the experimental procedures implemented for the batch MLSS settling test. The MLSS sample condition, sample modifications, container size, settling parameters required, as well as the test method, all play a role in the calculated SVI test results.

Table 2-3 Reported SVI test deficiencies or limitations

Feature	Deficiency	Reference
MLSS sample condition		
MLSS concentration	SVI highly dependent on MLSS, inconsistent relationship	Dick and Vesilind, 1969
Rheological characteristics	SVI not related to yield strength or to rheological properties	Dick and Vesilind, 1969
Filaments	SVI not well related to filament number or length	Blackbeard <i>et al.</i> , 1986
MLSS sample modification		
Temperature	SVI inverse power relationship at 5 to 45°C, inconsistent	Dick and Vesilind, 1969
Stirring	SVI reduce by gentle stirring, removes cylinder wall effects	Dick and Vesilind, 1969; Berkday, 1998
Dilution	SVI reduce by dilution, removes the MLSS concentration effect	Ekama and Marais, 1984
MLSS settling test cylinder		
Cylinder diameter	SVI dependent on cylinder diameter, according to MLSS properties	Dick and Vesilind, 1969
Cylinder depth	SVI dependent on cylinder depth, according to MLSS properties	Dick and Vesilind, 1969
MLSS settling parameters		
Initial settling velocity	SVI not related to ISV	Dick and Vesilind, 1969
Zone settling velocity	SVI not related to ZSV	Ekama and Marais, 1986
Settling profile response	SVI only dependent on one final point on settling profile	Dick and Vesilind, 1969
MLSS settling test method		
Batch method	Frequency of tests usually only once per day	Vanrolleghem and Lee, 2003
On-line method	Equipment not readily available for continuous monitoring	Sekine <i>et al.</i> , 1989

Ignorance or confusion continues to exist regarding the most suitable procedure for the SVI test, according to the different methods and equipment used in the reviewed literature. Bye and Dold (1998) contribute this uncertainty in part to the prescribed SVI test procedure (APHA, 1998) that changed in 1980. The basic quiescent MLSS sample settling method was then modified to include slow stirring at 1 to 2 revolutions per minute

(rpm) of the MLSS sample. The SVI test procedure (method 2710D; APHA, 1998) is, strictly speaking, a stirred specific volume index (SSVI) procedure, but it is designated as a SVI. This procedure further states that the T_s of the MLSS sample must be maintained at T_r during a SVI test, without providing implementation guidelines.

Table 2-4 SVI test method according to APHA (1998)

Test component	Method	Remarks from literature
Container size and type	1 l cylinder	Volume and shape (diameter and height) varies
Stirring	1 to 2 rpm	Samples are unstirred or stirred
Temperature	at T_r	No T_s information or T_s compensation and control for change from T_r
Test duration	30 minutes	Standard duration not changed
Container material	not stated	Material and wall thickness varies
MLSS sample source	not stated	Taken at BNR reactor outlet

A summary of the variables of the SVI test method (APHA, 1998) is provided in Table 2-4. In literature, the prescribed SVI test method modifications usually involve any combination of three of the six test components, which are (i) container size, (ii) stirring, and (iii) temperature compensation:

(i) The zone settling velocity of MLSS samples (stirred or unstirred) could be affected by the settling container size (diameter and height), depending on the MLSS characteristics. Renko (1996) concludes that a suspension with a low MLSS concentration settles faster in a small diameter cylinder, due to liquid streaming up the cylinder walls. A suspension with a high MLSS concentration settles slower in such a small diameter cylinder as a result of biofloc bridging and support. (ii) Ekama *et al.* (1985) state that gentle MLSS sample stirring reduces cylinder wall effects, short-circuiting, as well as MLSS concentration effects. The MLSS concentration effects reduce mainly due to better biofloc agglomeration during stirring (Vanrolleghem and Lee, 2003). Nevertheless, sample stirring does not completely overcome the effect of MLSS concentration, as demonstrated by Dick and Vesilind (1969) with different MLSS samples. (iii) Details of prescribed equipment and methods to compensate for temperature changes during MLSS settling tests are absent from the available literature.

Bye and Dold (1998) and Lilley *et al.* (1997) confirm that SVI tests for routine use are usually performed at room temperature in a laboratory, and more often than not with an

unstirred MLSS sample. The continued use of the unstirred SVI at room temperature can be attributed to the simplicity and convenience of the SVI method (Schuler and Jang, 2007), as specialised equipment and procedures for stirring and in particular temperature compensation are not readily available for routine use.

2.2.4.2 Alternative indexes

Ekama *et al.* (1985) and Daigger (1995) promote the replacement of SVI, in process design as well as plant operation and control, by alternative indexes. The most common modifications to the standard SVI include sample stirring or sample dilution, or both. A standard SVI test with sample stirring is named a SSVI. A MLSS sample dilution changes a SVI to a diluted SVI (DSVI). Ekama and Marais (1984) provide guidelines for SVI determinations at a fixed MLSS concentration of 3.5 g/l (unstirred SVI_{3.5} or stirred SVI_{3.5}), as well as a DSVI test method.

Table 2-5 Alternative MLSS settling indexes

Index name		Procedure
SVI _{3.5}	SVI at standard MLSS concentration of 3.5 g/l	SVI test is performed at a fixed MLSS concentration of 3.5 g/l by sample dilution
SSVI	Stirred specific volume index	Test cylinder is equipped with a slowly rotating stirring device (about 1 rpm)
SSVI _{3.5}	Stirred specific volume index at standard MLSS concentration	SSVI test is performed at a fixed MLSS concentration of 3.5 g/l by sample dilution, 2.6 l column
DSVI	Diluted SVI	Sample dilution to obtain a SV ₃₀ value smaller than 200 or 250 ml (Bye and Dold, 1998) after 30 minute MLSS settling, 1 l cylinder

These alternative settling indexes are summarised in Table 2-5 (adapted from Cloete and Muyima, 1997). The DSVI is performed in a 1 l graduated cylinder, and the SSVI_{3.5} in a 2.6 l column. The recommended depth to diameter ratio for tall columns are prescribed at greater than 9:1, but recommended ratios for graduated 1 l cylinders are absent. Temperature compensation procedures are not supplied in the available literature for the determination of any of the alternative indexes. These settling index test procedures only address MLSS sample stirring, and in some instances the size of the settling container.

The use of alternative indexes, specifically the DSVI, can change the MLSS sample characteristics. Chaignon *et al.* (2002) caution that MLSS sample dilution for the DSVI test, with a supernatant of different ionic strength such as potable water, could lead to deflocculation. Unchlorinated secondary clarified effluent is a suitable dilution medium for the DSVI test (Jeyanayagam *et al.*, 2006). The effects of temperature changes during this MLSS sample dilution with plant effluent are not adequately addressed in available research reports. A DSVI test extends the SVI range (White, 1976), as the dilution reduces the MLSS concentration, but DSVI does not consider the MLSS compression characteristics. White, as cited by Ekama and Marais (1984), proposed the use of the SSVI_{3.5} (at a fixed MLSS concentration of 3.5 g/ℓ), as the SSVI is not always independent of MLSS concentration.

Daigger (1995) cautions that there is not sufficient reference data available to develop improved empirical correlations for these alternative indexes, when compared to the large collection of available SVI data. Operational and research reference data in the literature is generally related to SVI (Mines and Horn, 2004), with fewer case studies using alternative indexes. The effects of temperature variations on these alternative settling indexes are not available. The alternative settling index interpretation depends accordingly on experimental conditions, as is applicable to SVI.

2.2.4.3 Future SVI use with settling parameters

Akça *et al.* (1993) confirm that SVI is still a useful and a valuable indicator of MLSS settling and thickening characteristics. Several South African treatment plants perform SVI tests as the only routine indicator to monitor MLSS settleability (Casey and Alexander, 2001). SVI is also extensively used in various modelling applications. MLSS settling characterization that precedes MLSS settling model selection is often based on SVI (Vanrolleghem *et al.*, 2003), due to SVI data and model availability. Such SVI-based models are used in several applications, amongst others to predict settleability failures (Banadda *et al.*, 2005). Recently, Martínez *et al.* (2006) developed a case-based reasoning tool for MLSS separation, and SVI is included as a quantitative indicator of MLSS settleability. The simplicity of the SVI test is the main reason for its continued extensive use in these various operational and modelling applications (Akça *et al.*, 1993), despite all the publicised shortcomings.

Table 2-6 Experimental conditions for SVI use in settling parameter correlations

Parameter	Cylinder size	T _r , T _s , T _a	Stirred	Reference
Minimum ZSV	1 ℓ	Unknown	No	Bhargava and Rajagopal, 1993
Sonification time	1 ℓ	Unknown	Unknown	Bieñ <i>et al.</i> , 2005
Tank bottom SS concentration	1 and 2 m tall columns	Unknown	Unknown	Kazami and Furumai, 2000
Tank average SS concentration	1 ℓ	Unknown	1 rpm	Kim <i>et al.</i> , 1997
Biological and physico-chemical parameters	Unknown	Unknown	SSVI _{3.5}	Sponza, 2004

Several SVI-based parameter correlations, as summarised in Table 2-6, are used for operational process control, design and modelling. SVI is correlated in five different applications, as listed in Table 2-6, to settling velocity, sonification time (ultrasonic floc disintegration time), settled and suspended MLSS concentration, and biofloc properties. SVI is included as an independent variable in all of these correlations, but once again without any temperature related reference information.

2.2.5 SVI and settling velocity correlations

MLSS settling proceeds through different settling velocities (Zhang *et al.*, 2006a) during a 30-minute test period. Discrete, zone settling, and compression settling velocities are three separate processes taking place. The zone settling velocity is considered as a key parameter, due to its use in design and operational MLSS settling control.

Most empirical ZSV models include MLSS concentration as the only independent variable, although a variety of mathematical expressions with calibrated constants are used (Smollen and Ekama, 1984). The exponential Vesilind function is the most widely used model, and it links the maximum MLSS settling velocity to the MLSS concentration (Grijpspeerdt *et al.*, 1995) as follows:

$$V_s = v_o \cdot e^{-n \cdot X}$$

where V_s represents ZSV, X represents the initial MLSS concentration, and v_0 and n are MLSS-specific settling constants.

The MLSS settling constants v_0 and n define settling characteristics (Daigger and Roper, 1985). These constants require calibration to reactor process conditions and MLSS properties for each plant reactor (Bergh, 1996). The ZSV is also named constant- (Bhargava and Rajagopal, 1993), hindered- (Dupont and Dahl, 1995), highest- (Gernaey *et al.*, 1998), relative- (Bergh, 1996), or maximum settling velocity (Lynggaard-Jensen and Lading, 2006). The v_0 constant is also named initial settling velocity (Lynggaard-Jensen and Lading, 2006). These numerous terms used for constants indicate that detailed MLSS settling test information is required to ensure parameters are interpreted correctly.

Catunda and Van Haandel (1992) found that parameter values that characterise MLSS settleability exhibit considerable oscillations around average values. This noticeable scatter in experimental settling results is frequently reported (Kristensen *et al.*, 1994). Daigger and Roper (1985) found likewise a great deal of experimental data scatter, and they had to separate SVI data in four SVI ranges to obtain better correlation results.

Table 2-7 Experimental conditions for SVI use in settling velocity correlations

Parameter	Empirical equation	Reference	Cylinder	T_r T_a T_s	Stirred
Settling velocity, V_s	$V_s = 7.80e^{[-0.148 + 0.00210 \cdot (SVI)] \cdot X}$	Daigger and Roper (1985)	1 l	Unknown	1 rpm
Settling velocity, V_s	$V_s = (17.4e^{-0.00581 \cdot SVI} 3.931) \cdot \exp(-(-0.9834 \cdot e^{-0.00581 \cdot SVI} + 1.043) \cdot X)$	Härtel and Pöpel (1992)	Not stated, equation was compiled from various data sources		
Settling velocity, V_s	$V_s = (28.1 (SVI)^{-0.2667}) \cdot \exp(-(0.177 + 0.0014 \cdot SVI) \cdot X)$	Akça <i>et al.</i> (1993)	Not stated, equation was compiled from various data sources		

Empirical correlations between ZSV and SVI attempt to make MLSS settling predictions easier. The SVI-based settling velocity correlations listed in Table 2-7 illustrate the additional uses of SVI in MLSS settling correlations, as well as the continued lack of temperature related reference data.

None of the previous studies explicitly addresses temperature fluctuations as a possible contributing factor to variations in the empirical MLSS settling correlations results. The extent of temperature variations under operational and laboratory test conditions must be determined to consider the possible impact of temperature on MLSS settling.

2.3 Operational plant temperature conditions

2.3.1 Overview

Various T_r variation models have recently been developed. Wells *et al.* (2005) describe several model improvements to allow plant designers and operators to predict reactor and plant effluent temperature variations. These models are developed in order to design treatment plant structures to avoid low T_r conditions, or to reduce the heat load from the final effluent discharge to rivers during cold winter months (Makinia *et al.*, 2005). These T_r -based model developments are for the most part unrelated to MLSS settleability, as correlations between modelled T_r fluctuations and MLSS settleability variations have not been considered in the available literature.

2.3.2 Modelling temperature variations

Makinia *et al.* (2005) present reviews of several dynamic T_r models that predict temperature fluctuations in full-scale reactors. Several energy contributions of heat gains and losses that influence this T_r are summarised in Table 2-8, according to model components provided by Gillot and Vanrolleghem (2003) and Makinia *et al.* (2005).

These T_r models illustrate the extent of temperature variations possible at a treatment plant. Table 2-8 indicates that, although the raw sewage plant inlet temperature (T_{raw}) component is the largest single contributor to T_r , the combined site-specific conditions have a larger influence on T_r . The contribution of energy components can change on a short- and a long-term basis, according to local conditions. For example, cloud cover and

shading have a direct effect on the contribution from solar radiation (Scherfig *et al.*, 1996).

Table 2-8 Typical range of energy contributions to influence T_r

Energy transfer phenomena	Temperature change [°C/day]
<i>Significant energy contributions:</i>	
Sensible heat (inflow)	0.5 to 3.5 decrease or increase
Solar radiation	0.5 to 2.5 increase
Surface evaporation	0.5 to 2.5 decrease
Process energy (exothermic biochemical reactions)	0.5 to 2.0 increase
Atmospheric radiation	0.5 to 1.0 decrease
<i>Insignificant energy contributions:</i>	
Precipitation (rain and snow on surface)	<0.2 decrease or increase
Mechanical energy (aerators and mixers)	<0.1 increase
Geothermal energy (basin wall convection and conduction)	<0.05 decrease or increase

An overview of temperature data for raw wastewater, reactors, secondary settling tanks, as well as the surrounding environment (ambient), provide an indication of the expected range of operational temperature variations. These variations will contribute towards the change from T_r to T_s during batch MLSS settling tests, as well as temperature-based MLSS settling changes in reactors and secondary settling tanks.

2.3.2.1 Ambient temperature

Observations by Banks *et al.* (2003) confirm that short-term T_a fluctuations follow diurnal sinusoidal profiles. These T_a profiles are mirrored, with a lag period, by changes in temperatures of affected water bodies, such as plant T_r . There will be damping effects present in these T_r profiles with increased depth, if the reactor content is not well mixed.

Sinusoidal profiles are also present in long-term (seasonal) T_a changes, as illustrated in Figure 2-2. The meteorological data for Johannesburg, South Africa, provides an average diurnal T_a fluctuation of 12°C, based on monthly averages over a 30-year period (South African Weather Service, 2007). The average fluctuation moves from an average daily minimum of 10°C to an average daily maximum of 22°C, as illustrated in Figure 2-2. The lowest and highest recorded T_a is -8°C and 35°C respectively, as measured in winter (June) and summer (January).

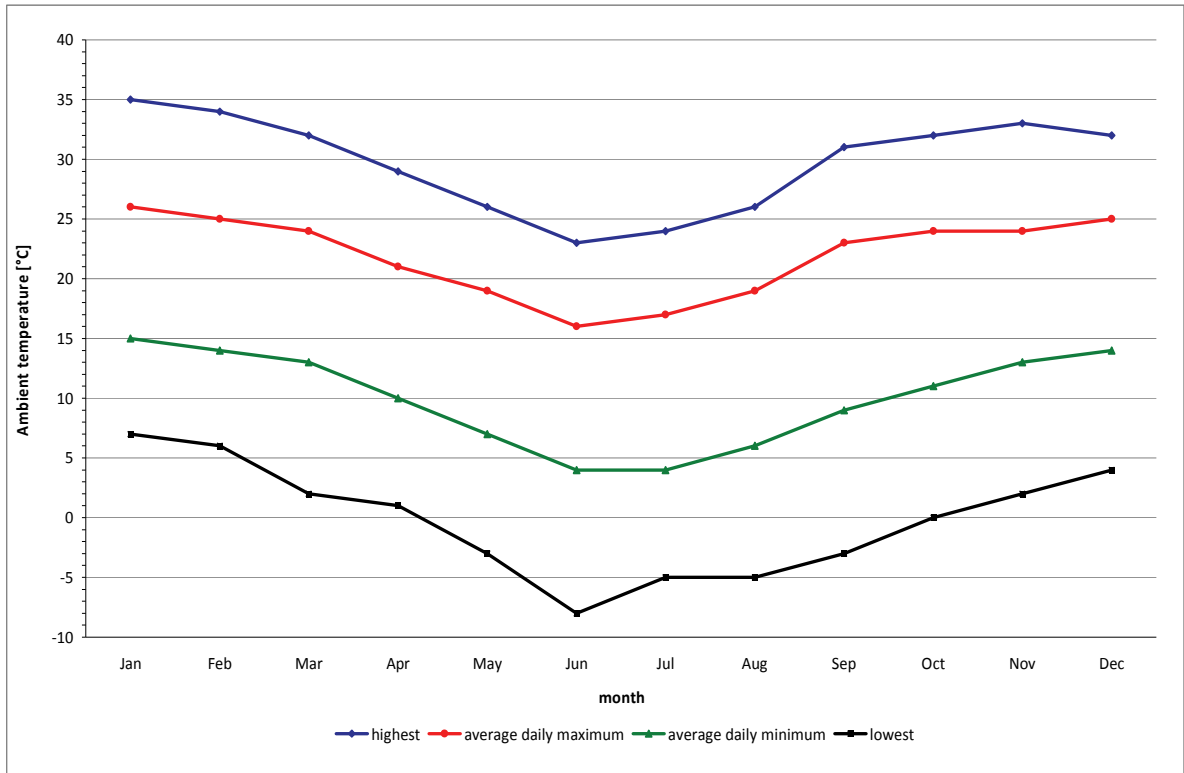


Figure 2-2 Annual T_a profiles for Johannesburg, South Africa

2.3.2.2 Raw wastewater temperature

There is limited information available about the short-term and long-term changes in T_{raw} . These T_{raw} variations are due to cyclic domestic water uses and industrial processes, with additional contributions from industrial process unit shut-downs and start-ups (Morgan-Sagastume and Allen, 2003), as well as seasonal climate changes. Short-term meteorological conditions should also influence T_r , but this could not be confirmed from the available literature. T_{raw} variations are plant specific, but T_{raw} data is usually not required for plant performance monitoring.

Wahlberg *et al.* (1996) demonstrate the extent and influence of unique plant specific T_{raw} variations with a case study. An average winter T_r reduced subsequently in spring by 2°C , from 10.3°C to 8.3°C , due to the colder snowmelt inclusion in a wastewater plant inflow. A guideline for industrial effluent contributions to sewer networks limit the maximum discharge temperature to 45°C (IWPC, 1977), although T_{raw} was at that stage not related to T_r .

2.3.2.3 Reactor temperature

The long-term average T_r fluctuation for design calculations in South Africa has been approximated as 8°C (WRC, 1984), based on a minimum and maximum T_r of 14 and 22°C respectively. Osborn *et al.* (1986) reported the same seasonal T_r measurements, of 14 and 22°C, for a plant in Johannesburg. Long-term T_r variations of up to 13°C have been detected in European plants, such as 7 to 20°C for the Klaby plant in Sweden (Ingildsen, 2002), as well as 9 to 22°C for the Katwoude plant in the Netherlands (Janssen *et al.*, 2002). The long-term T_r fluctuations are subject to individual plant conditions and seasonal meteorological conditions.

Psychrophilic, mesophilic, and thermophilic bacteria function in low (0 to 15°C), medium (15 to 40°C), and high (40 to 75°C) temperature ranges respectively (Droste, 1997). No single organism will grow over all three temperature-ranges, although MLSS bacteria can tolerate short-term exposure to high temperatures (Archibald and Young, 2004). Temperature exerts a selective pressure to create medium- to long-term microbiological population shifts (Erdal, 2002). Most municipal wastewater treatment plants operate in the psychrophilic or lower mesophilic temperature range, while industrial effluent plants such as pulp and paper mills operate in the higher mesophilic or thermophilic range (Archibald and Young, 2004). Long-term MLSS settleability evaluations outside the operational T_r range can produce inconsistent settling test results, due to microbial population shifts.

Bubble or diffused air aeration reactors have higher T_r than comparable surface aeration reactors, due to the addition of warm compressed air that can reach 85°C at source (Maqueda *et al.*, 2006). Pitman (1991) observed that a plant with a bubble aeration system produced MLSS with excellent settling properties, at maximum 60 mL/g DSVI, against DSVI values of up to 300 mL/g at two nearby plants equipped with mechanical surface aeration systems. Parker (2004) contributed this improved settleability to the superior air and dissolved oxygen (DO) distribution of bubble aerators. The influence of higher T_r in bubble aeration reactors on MLSS settleability is not documented in the available literature.

Scherfig *et al.* (1996) observe frequent T_r drops of 2 to 3°C over a few days when winter weather patterns in Europe change rapidly. The diurnal T_r fluctuation is in the range 0.5 to

1.0°C (Makinia *et al.*, 2005). The temperature change from the reactor inlet to outlet is measured at a plant at about -1.0 to 0.5°C in winter, compared to 0.5 to 1.5°C in summer. These T_r variations are once again subject to individual plant conditions.

2.3.2.4 Secondary settling tank temperature

The formation of concentration and thermal density currents in secondary settling tanks are created by SS concentration and temperature differences (De Clercq *et al.*, 2003). These temperature differences are as small as 0.2°C. Taebi-Harandy and Schroeder (2000) experimentally confirmed these small temperature differences, as well as related settleability changes. The MLSS inflow from the reactor, the MLSS in the settling tank, the return activated sludge (RAS), the clarified effluent from the tank, as well as the top surface effluent layer, all exhibit different temperatures that can be related to T_a (Tadesse *et al.*, 2004). Density currents cause short-circuiting (Kim *et al.*, 2003) as MLSS inflow moves over dead space (when warmer and lighter) or under dead space (when colder and heavier) inside a secondary settling tank.

Denitrification in a secondary settling tank is regulated by the NO_3^- and NO_2^- concentration and the sludge residence time (Azimi and Horan, 1991). There is furthermore a correlation between temperature and the denitrification rate, as the buoyancy of gas bubbles increases by 15% for a temperature increase of 10°C (Ekama *et al.*, 1997). Sarioglu and Horan (1996) determined that the gas bubble size is dependent on temperature. At lower temperatures (<15°C), the small gas bubbles result in a critical nitrogen concentration (rising sludge) of 13 to 16.5 mgN/ℓ that decreases to about 8 to 13 mgN/ℓ at higher temperatures. Settled MLSS stability is therefore temperature dependent.

Solar radiation (Schutte, 2006) and changing wind patterns (Van Der Walt, 1998) create diurnal temperature changes in secondary settling tanks. Kim *et al.* (2006) modelled the effect of these diurnal temperature fluctuations on MLSS settling flow patterns. A positive heat flux is created by daytime solar radiation once T_a is about 2°C warmer than the tank MLSS influent. This temperature increase results in density currents and cascading flow patterns. Conversely, a negative heat flux is created by nighttime and winter surface cooling once T_a is 2°C cooler than the tank MLSS influent. This temperature decrease results in buoyant flow, a surface current and significant short-circuiting. Jokela and Immonen (2002) studied the impact of the lower winter water

temperatures (3 to 12°C) on activated sludge clarification in a chemical-industry wastewater treatment plant. They observed sludge settling deterioration and ultimate sludge carry-over during variable and lower temperatures. These results confirm the general hypothesis of the direct link between MLSS settleability and temperature.

The temperature dependent MLSS settling process in a secondary settling tank is simulated by manual batch MLSS settling tests. The temperature impact on these settling tests in containers will vary according to the procedures and equipment used.

2.4 Batch MLSS settling tests and temperature variations

Batch MLSS settling tests should preferably be carried out on-site as soon as possible after the MLSS sample is collected (Ho *et al.*, 2006). The immediate testing of MLSS samples ensures the sample is fresh (Ekama, 1988). Wilén (1999) recommends that T_s is as close as possible to T_r during settling tests, as storage (specifically at 4°C) results in a reduction in microbial activity and a larger tendency of the MLSS to deflocculate. Neither T_s nor T_a is as a rule regulated or monitored during batch MLSS settling tests. Research reports mention occasionally that a settling test is performed at laboratory or room temperature (Chaignon *et al.*, 2002). Constant room temperatures are in such cases assumed, if not specified (Grijpspeerdts and Verstraete, 1997; Hercules *et al.*, 2002).

Most research reports disregard the requirement to create uniform temperature conditions throughout the MLSS settling container content. Tchobanoglous *et al.* (2003) caution against T_s variations inside large settling columns. For this reason, Clements (1976) insulates settling columns with polystyrene to minimise changes to T_s . Simon *et al.* (2005) specifies a maximum 2°C difference between T_s and T_a to minimise the effects of convection on MLSS settling. These references appear to be the only reports available in the literature to address the control of T_s inside settling containers.

Different types and sizes of containers are used for batch MLSS settling tests. Tchobanoglous *et al.* (2003) describe these containers as 1 or 2 ℓ graduated cylinders or 2 ℓ settlometers (usually wider than 2 ℓ graduated cylinders), as well as larger settling columns. These columns vary in size, from 1.8 m (Bye and Dold, 1999) to 3 m (Clements, 1976) tall. The basic 30-minute batch MLSS settling test in such a container is the short-

term simulation of the reactor MLSS settleability. The MLSS obtained from the reactor settles subsequently in a downstream secondary settling tank.

2.5 On-line MLSS settling tests and temperature variations

It is not realistic to measure MLSS settling in an operational secondary settling tank (Forster and Dallas-Newton, 1980), as the liquid to MLSS interface blanket height changes according to the hydraulic load on the settling tank. An *in situ* MLSS settling test approach is recommended, which suggests on-line MLSS settling measurements at the reactor. Rasmussen and Larsen (1997) state that such semi-continuous on-line methods can identify variations in MLSS settling properties that are not easily detected with batch settling tests.

Vanrolleghem and Lee (2003) find the scarcity of on-line instrumentation for MLSS settling monitoring in wastewater treatment plants surprising. They blame this monitoring deficiency on the lack of fundamental insights in the determination of MLSS settling factors. Grijspeerdt *et al.* (1995) recognise that specific research from the early 1990s attempts to develop reliable on-line MLSS settling sensors. This technological progress results in the development and implementation of novel sensors, suitable for aspects of on-line settleability monitoring and control.

2.6 Summary

The MLSS settling process depends on the MLSS concentration and the flocculation tendency of SS particles. The flocculation tendency is governed by complex physical, chemical, and biological interactions. Temperature has opposite effects on these physical and biological changes, and MLSS settleability changes are therefore difficult to predict.

Several parameters represent the MLSS settleability, with SVI still regarded as the most widely used parameter, in spite of several limitations. Alternative indexes have been developed, but SVI is still preferred for routine and modelling use, mainly due to the simplicity and convenience of the experimental test procedure. The lack of reported temperature data in MLSS settling test results, although required by recommended

methods, suggests that temperature compensation is not performed during these experimental procedures.

Existing plant temperature models include energy components that contribute to create site-specific T_r profiles. These T_r profiles usually mirror with lag the short- and long-term T_a fluctuations. MLSS settling is very sensitive to meteorological conditions at full-scale secondary settling tanks. It is obvious that these conditions, specifically temperature, wind, and sunshine, will have a similar significant influence on batch MLSS settling test results. Inadequate information was found in the available literature on the use of batch settling equipment with temperature compensation facilities to manage changes from T_r to T_s , due to the influence of T_a .

Automated MLSS settling meters are suitable equipment for on-line MLSS settleability evaluations. Surprisingly, the reported on-line settling meter applications over diurnal T_r fluctuations excluded temperature-based MLSS settling models. On-line monitoring of MLSS settling during these diurnal temperature fluctuations provides as a result an opportunity to correlate possible relationships between MLSS settling parameters and temperature.

2.7 Conclusions

The review of the literature, relating temperature to MLSS settling, indicates that there is a lack of reported MLSS settling data subject to short-term temperature fluctuations. The following conclusions are based on the literature survey:

- Hindered MLSS settling requires empirical correlations that are developed from experimental data. Hindered MLSS settling correlations that incorporate T_s or T_r are not available from the literature survey.
- MLSS settling parameters are determined from basic batch MLSS settling tests, based on standard methods that require the implementation of temperature compensation. Details of methods or temperature compensation equipment are not provided in the literature survey.

- Reactor temperature models are available for short- and long-term temperature fluctuation simulations. It appears from the literature that MLSS settling aspects are not incorporated in these temperature models.
- SVI is still the most prevalent settling index used by operators, although the deficiencies, amongst others a significant temperature reliance, has been reported for more than 75 years. T_r recordings and T_s compensation procedures during batch MLSS settling tests are absent from the reported literature. Suitable settling equipment details, to compensate for short-term temperature effects, are also not readily available.
- Numerous settling models provide relationships between SVI and MLSS settling velocity. It appears from the literature that temperature compensation is absent from these MLSS settling models.
- A small number of on-line MLSS settling meters have been developed and successfully tested in pilot and full-scale reactors. These settling meters have, however, not been utilised to identify MLSS settling parameter relationships based on short-term temperature fluctuations.

MLSS settling dependence on temperature variations are sufficiently demonstrated in the literature survey to merit proceeding with the rest of the research program, as represented by the research aims.

2.8 Research aims

The purpose of this project is to demonstrate that short-term temperature variations are an essential component of traditional MLSS settling determinations. Consequently, this research focuses on three aspects, owing to their relevance to MLSS settling tests and monitoring, combined with the identified lack of operational temperature information from the literature review:

- The magnitude of short- and long-term temperature variations will be established with a plant survey. Significant T_r variations will confirm the need to determine the impact of T_r fluctuations on MLSS settling parameters.

- Batch MLSS settling tests will establish the sensitivity of settling parameters to environmental conditions. The extent of parameter variations will indicate if the current lack of temperature compensation or reference temperature data in MLSS settling tests requires future equipment and procedure improvements.
- On-line MLSS settling evaluations will be conducted on pilot and full-scale reactors to establish the effect of diurnal T_r fluctuations on MLSS settling parameters. The temperature-based settling parameter correlations will be compared to the MLSS concentration-based correlations to evaluate the impact of T_r inclusion. T_r -based settling parameter modelling will be based on best-fit and simplified curve-fitting procedures to illustrate the effects of short-term T_r variations on MLSS settling.

The above-mentioned research aims are individually addressed in the subsequent chapters.

3 TEMPERATURE OBSERVATIONS

Temperature variations, identified from an exploratory survey at five plant reactors, are presented in this chapter. The extent of long- and short-term temperature variations illustrates typical operational temperature variation ranges. This temperature data complements the limited published information obtained from the literature survey.

3.1 Background

T_r is subject to short-term (hourly to diurnal) and long-term (weekly and monthly to seasonal) variations (Wahlberg *et al.*, 1996). Makinia *et al.* (2005) modelled these T_r variations as sinusoidal profiles that follow cyclic nighttime and winter cooling stages, between daytime and summer heating stages. The long-term T_r fluctuations are related to T_a fluctuations, which vary according to the geographical position of the plant. These long-term T_r ranges extend from 5 to 10°C during winter in Northern Europe and Canada to over 30°C during summer in Asiatic countries (Oldham and Rabinowitz, 2002; Tandoi *et al.*, 2006). Such T_r fluctuations have a direct influence on MLSS settling. Improved MLSS settling is recorded during the warmer summer months, followed by transition periods during spring and autumn (Kruit *et al.*, 2002), with poorer MLSS settling evident in the colder winter months.

Long-term T_r variations govern several aspects of biological processes, such as the rate of reactions (Krishna and Van Loosdrecht, 1999), the growth rate of all bacteria and in particular nitrifying bacteria (Barnard, 1974), as well as the selective development of specific microorganism populations (Grady and Filipe, 2000). The theoretical reaction rates for most of these biological processes double for each 10°C temperature increase up to a maximum temperature (Dochain and Vanrolleghem, 2001). Some full-scale process reaction rates could be less temperature sensitive (Pöpel and Fischer, 1998) due to inhibiting factors.

Long-term T_r variations also influence the physical properties of MLSS. As MLSS is mainly composed of water and bioflocs (Wilén *et al.*, 2006), physical MLSS properties relate to water characteristics such as density and viscosity, as well as biofloc characteristics such as density, size, and shape (Scuras *et al.*, 1998). Short-term T_r variations influence accordingly the physical properties of MLSS.

Short-term T_r fluctuations are not routinely used as an operational process performance parameter. Diurnal T_r fluctuation effects on MLSS settleability are therefore not recorded or correlated to process performance. The average daily T_r of 14°C in winter and 22°C in summer for South African weather conditions are used as T_s for modelling exercises (WRC, 1984). The extent of MLSS T_s changes due to the influence of T_a , as well as the final difference from T_r , after a time delay due to MLSS sample collection, transfer, storage, and settling during batch tests, has not been reported in any detail in the available literature.

The aim of this chapter is to establish a typical range of plant temperature fluctuations. The differences between T_r and T_a illustrate temperature variations that can be expected between plant reactors and settling test container samples under the influence of T_a .

3.2 Materials and methods

3.2.1 Experimental approach

T_r readings are recorded with hand-held or on-line thermometers at five different BNR reactors. On-line readings are continuously recorded and stored in data loggers to capture T_r profiles. These profiles are required to establish the extent of short-term temperature variations found in batch and automated MLSS settling evaluations.

3.2.2 Temperature data collection

3.2.2.1 Plant reactors used for temperature observations

Batch and on-line temperature data was collected at five BNR reactors at two wastewater plants, as indicated in Table 3-1. The size of the reactors and the aeration method are listed, as these reactor attributes could influence T_r and the extent of diurnal T_r fluctuations.

Plant 1 contains two full-scale reactors (1a and 1b) with surface aeration systems, as well as a pilot plant (1c) with submerged bubble aeration. Plant 2 is located about 80 km from plant 1. Plant 2 includes adjacent surface aeration (plant 2a) and bubble aeration (plant

2b) reactors. This plant configuration offers the opportunity to identify effects of the aeration methods on full-scale T_r .

Table 3-1 Sizes of five BNR reactors in two plants used in temperature observations

Plant	Reactor	BNR reactor size [m ³]	Aeration method
1	a	25550	Surface
1	b	15000	Surface
1	c	1.8	Bubble
2	a	45500	Surface
2	b	31796	Bubble

3.2.2.2 Short- and long-term temperature variation

The on-line DO concentration meters (Royce Model 9100D; Royce, 1999) in plant 1 and 2 aerobic reactors include built-in temperature sensors. This temperature function is used to record once-off T_r readings during winter and spring at plant 1a, 2a, and 2b reactors.

These on-line DO concentration meters measure T_r continuously at plant 1b reactor. A similar DO meter was placed in the raw sewage inflow channel of plant 1 to record T_{raw} .

Data loggers (Fourier MicroLog Plus; Fourier, 2007) record the on-line data to produce diurnal T_r profiles. These data loggers contain internal temperature sensors to record T_a . Each logger produces separate T_a and T_r profiles.

3.2.2.3 Temperature data presentation

Microsoft Excel (Excel, 2007) is used to plot and trend T_a , T_r , and T_{raw} profiles in graphical format in 2-D graphs. The coordinate system consists of the horizontal x_1 -axis representing the time over several days or 24 hours, and the primary y_1 - and secondary y_2 -axes contain the temperature data.

3.3 Results and discussion

3.3.1 Long-term temperature variation

Typical long-term T_r variations that occur at wastewater treatment plants are summarised in Table 3-2. This data is based on manual recordings that are listed in Table 10-13 in Appendix B. Winter T_r of surface aeration plants 1a and 2a differ by about 2°C due to geographical and local conditions. The T_r of the bubble aeration plant 2b is about 5°C warmer at 17 to 18°C in winter, when compared to the T_r of the adjacent surface aeration plant 2a. Spring T_r increases by about 8°C for the surface aeration reactors of plant 1a and 2a, and by 5°C for the bubble aeration reactor of plant 2b.

Table 3-2 Seasonal and daytime temperature variations: surface and bubble aeration

Plant reactor	winter morning T_r [°C]	winter afternoon T_r [°C]	spring morning T_r [°C]	spring afternoon T_r [°C]
Reactor 1a	14.2	15.0	21.6	22.0
Reactor 2a	12.1	12.7	20.6	20.5
Reactor 2b	17.7	18.0	22.8	23.0

This T_r survey confirms the significant range of long-term T_r variations. The large T_r difference of more than 5°C between surface and bubble aeration at adjacent reactors of 2a and 2b has significant design and operational implications for temperature dependent BNR processes, as well as for aspects of MLSS settleability.

The T_r between morning and afternoon conditions changes by less than 1°C at all three reactors. This indicates that MLSS samples taken during this period of the day will have a relatively constant temperature, with variations of less than 1°C in T_r . The lower afternoon T_r of 20.5°C at reactor 2a is due to a rain event. Continuous T_r profiles are preferred to identify temperature variations that might not be detected with individual readings. The T_s should also be related to T_r for batch MLSS settling tests, as a variable T_a can change T_s before and during settling tests.

T_{raw} of plant 1 was monitored together with T_a for 42 days in spring, as shown in Figure 3-1. T_{raw} fluctuates by 4.3°C over a range from 16.3 to 20.6°C. The cyclic T_a profile shape is similar to T_{raw} over the 42-day period, with a total change of 27°C measured

from 12 to 39°C. The placement of the small data logger enclosure in direct sunshine contributed to this extended T_a range. The T_{raw} and T_a trends follow different slopes, with T_{raw} increasing as T_a is decreasing. These trends confirm that T_{raw} is influenced by local factors other than T_a , making it difficult to predict T_{raw} profiles from T_a data.

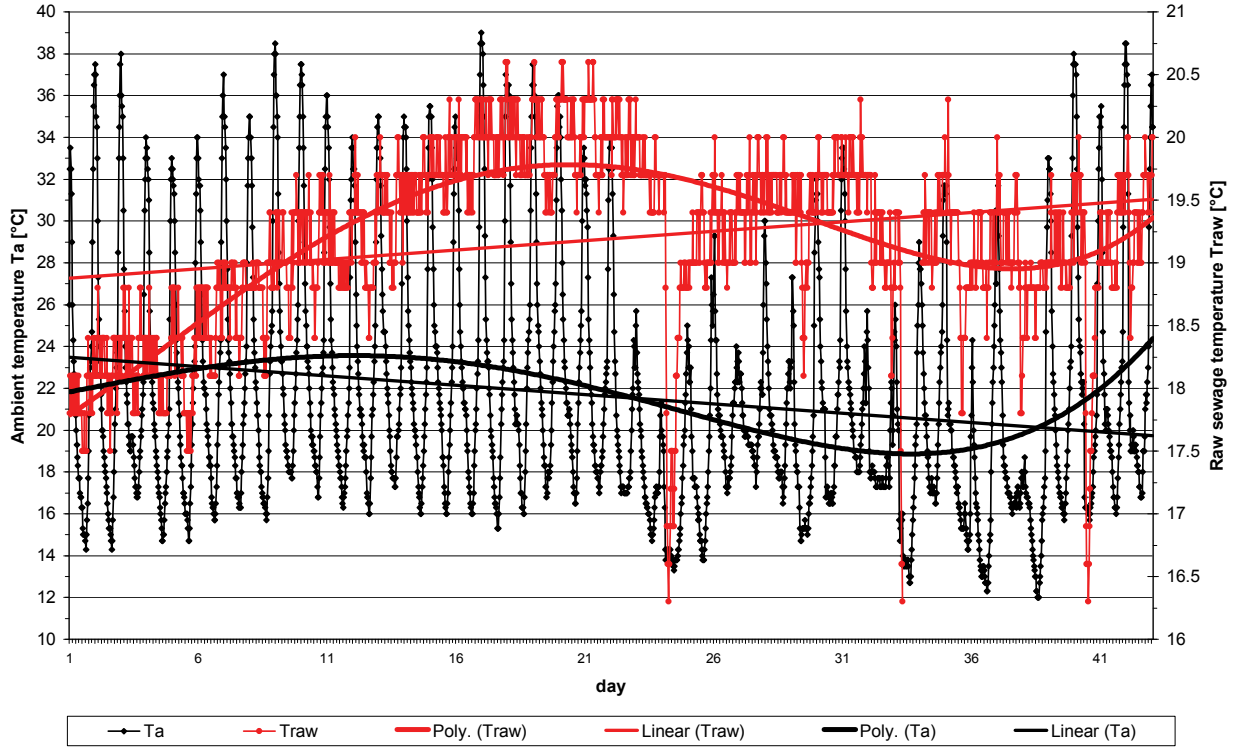


Figure 3-1 T_{raw} and T_a profiles over 42 days, plant 1

The T_r of plant 1a was monitored together with T_a for 19 days in spring, as shown in Figure 3-2. The T_r fluctuates by 2.8°C, over a range from 17.2 to 20.0°C. The cyclic T_a profile shape is similar, at a total change of 24.7°C, covering a range from 8.3 to 33.0°C. The T_r and T_a trends follow similar slopes, confirming that T_a directly influences T_r . The T_a fluctuations are mirrored by changes in T_r . These substantial T_r changes of a few degrees Celsius occurring over several days are thus related to T_a changes.

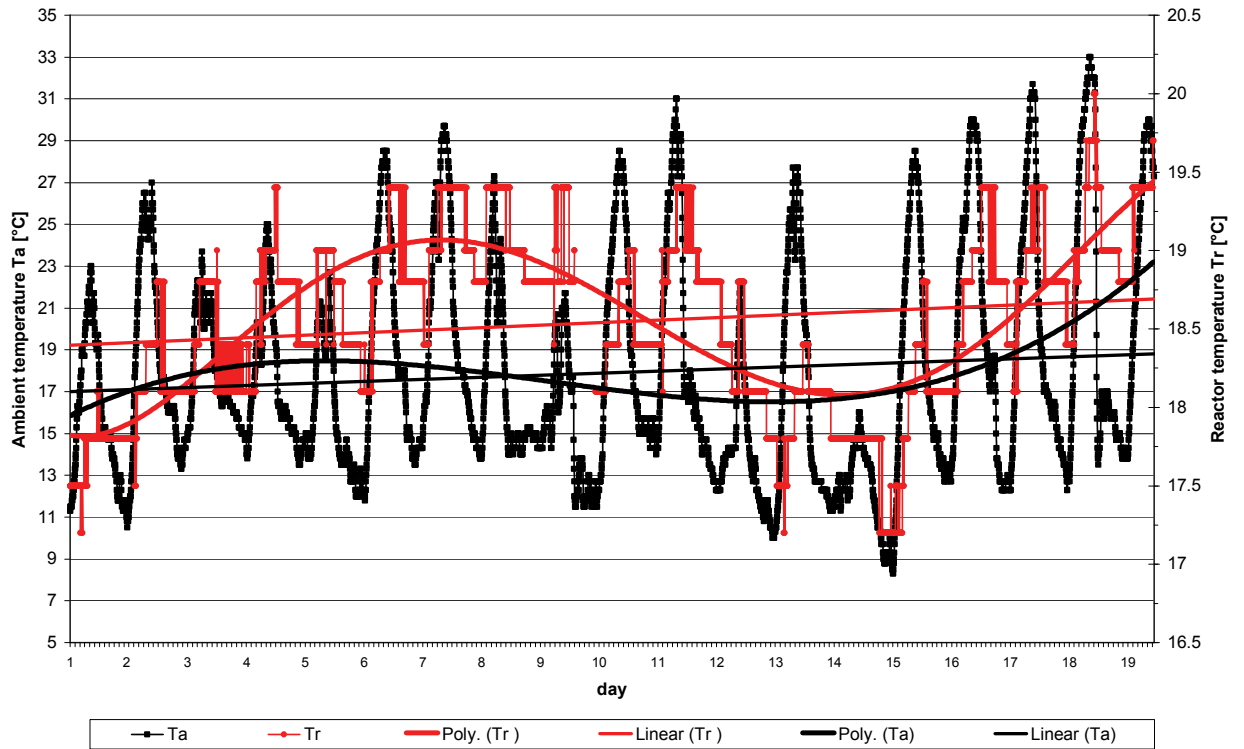


Figure 3-2 T_r and T_a profiles over 19 days, plant reactor 1a

The T_r and T_a recordings for the other two reactors at plant 1 over 10 days in spring show distinct diurnal temperature fluctuation trends. It illustrates and confirms the noticeable relationship between T_r and T_a , as shown in Figure 3-3. The T_r profile is connected by rising trend channels on the minimum and maximum daily T_r points, while the average T_r increase is shown with a linear trend line.

These trend channels indicate that the average T_r can change by approximately 4°C within 10 days. The diurnal T_r fluctuation range increases from about 16.5 to 18.0°C to about 19.0 to 20.5°C, while the average linear T_r trend changes by 2.75°C, from 17.25 to 20.0°C. The constant slopes of the trend channels show that the diurnal T_r profile fluctuation stays relatively constant at about 1.5°C.

The profile in Figure 3-3 also shows that the T_a increases from a diurnal variation range of about 12 to 32°C to about 16 to 30°C. The diurnal T_r variation of about 1.5°C is more constant than the diurnal T_a fluctuation that changes from about 20 to 14°C within a few days. The relationship between T_r and T_a is not constant, indicating that other factors and local conditions influence this relationship. These profiles are in good agreement with

profiles provided by Scherfig *et al.* (1996), when similar rapid temperature changes were recorded over a few days.

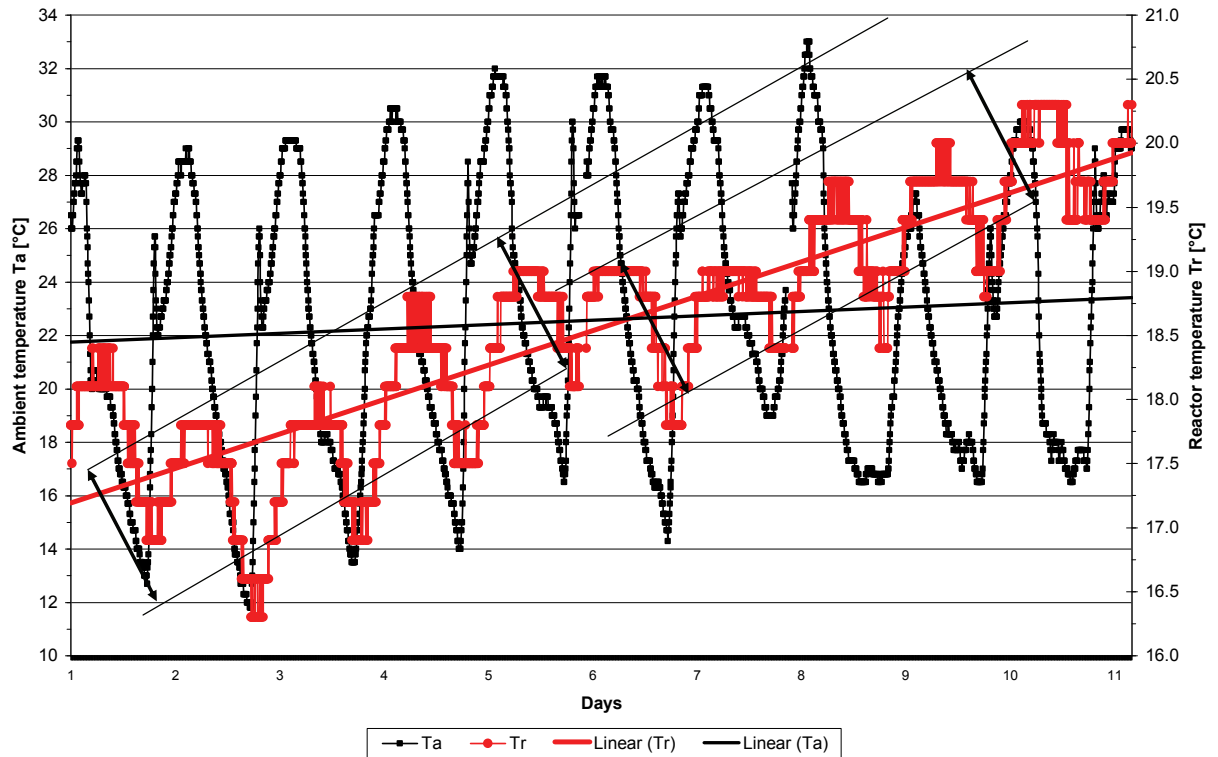


Figure 3-3 T_r and T_a profiles over 10 days, plant reactor 1b

The T_r and T_a recordings for the plant reactor 1c over an 11 day period during winter indicate more distinctive diurnal temperature fluctuation trends. It confirms the direct relationship between T_r and T_a for a smaller sized reactor, as shown in Figure 3-4. Rising trend channels on the minimum and maximum daily T_r points connects the T_r profile, and the average T_r increase is shown with a linear trend line.

The trend channels indicate that the average T_r can change by approximately 2°C within 10 days. The T_r diurnal fluctuation range decreases correspondingly from about 13 to 20°C to about 11 to 18°C, corresponding directly to the changes in the T_a . The steady slope of the rising trend channels shows that the diurnal T_r profile fluctuation stays constant at about 7°C.

The profile in Figure 3-4 shows that T_a decreases from a diurnal variation range of about 4 to 20°C to about 2 to 18°C. The diurnal reactor temperature variation of about 7°C follows the T_a diurnal fluctuation of about 16°C closely, due to the small reactor size.

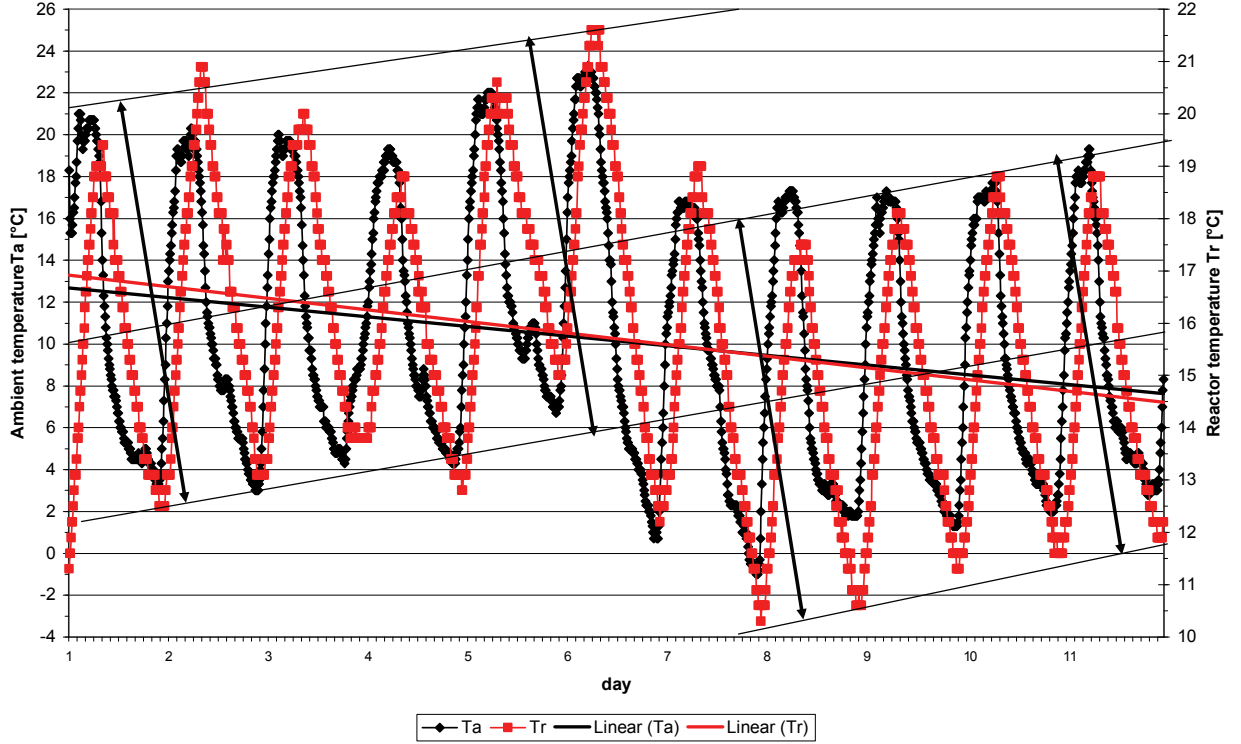


Figure 3-4 T_r and T_a profiles over 11 days, plant reactor 1c

3.3.2 Short-term temperature variations

The diurnal temperature variations for plant 1c in spring and plant reactor 1b in winter, as displayed in Figure 3-5 and Figure 3-6 respectively, illustrate the direct diurnal relationship between T_a and T_r . The T_a fluctuations are mirrored by changes in T_r , with a lag, which confirms the experimental observations of Banks *et al.* (2003).

A T_{raw} diurnal profile for plant 1 during winter, with a fluctuation of less than 1°C, is shown in Figure 10-38 in Appendix C. This profile indicates that the raw sewage temperature does not follow the diurnal T_a profile. T_{raw} cannot be represented by typical sinusoidal trends, as found in cyclic T_a and T_r fluctuations.

The T_a and T_r fluctuations for a spring day are represented by polynomials with $R^2 = 0.925$ and 0.918 respectively in Figure 3-5. The minimum T_a of 14°C occurs at about 06:00, and the maximum T_a of 31.8°C follows at about 15:30. The plant 1b minimum and maximum T_r are indicated from the data points as constant from about 05:00 to 10:00 at 17.5°C and 19:00 to 24:00 at 19°C respectively. These horizontal deviations from the sinusoidal profile are generated by the limited minimum recording limit of 0.3°C of the on-line thermometer logger. A 2-day profile is provided in Figure 10-52 in Appendix F for reference purposes. Two polynomial equations represent the T_a and T_r correlations with R^2 of 0.78 and 0.91 respectively for the fitted data.

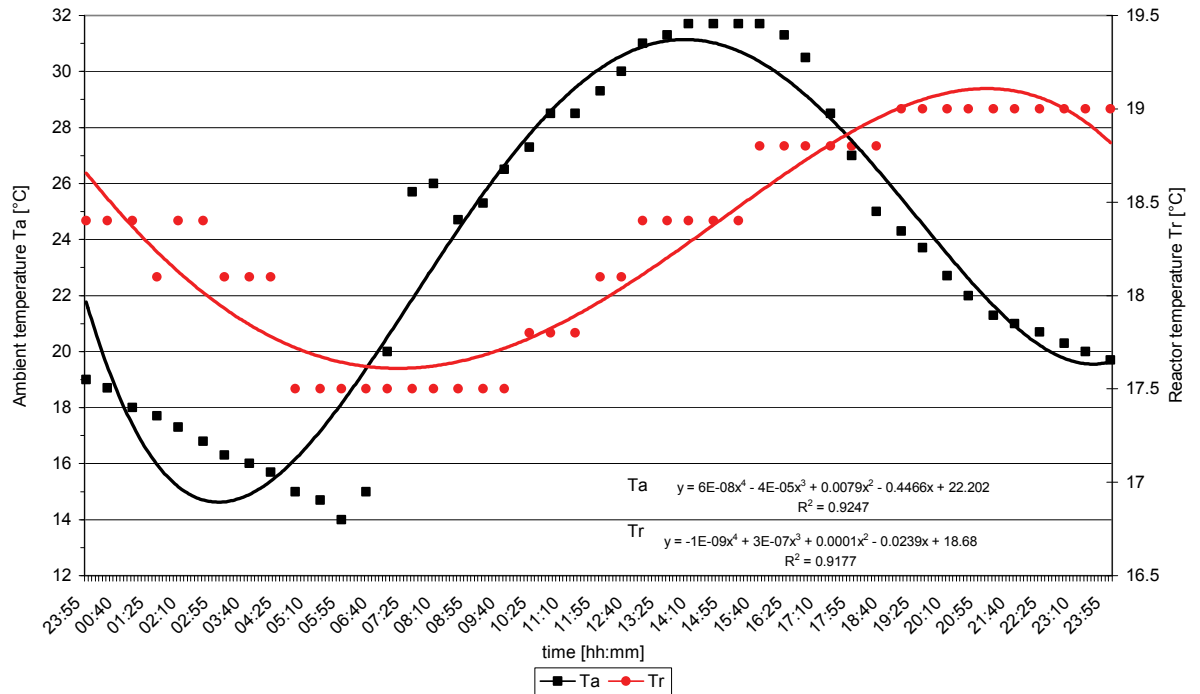


Figure 3-5 Diurnal T_r and T_a profile, plant reactor 1b

The T_a and T_r fluctuations are represented by polynomials with $R^2 = 0.904$ and 0.918 respectively Figure 3-6. The plant reactor 1c T_r profile lags behind the T_a profile by only 2.5 hours. The minimum T_r of 10.9°C occurs at about 08:30, and the maximum T_r of 17.2°C is recorded at about 21:00.

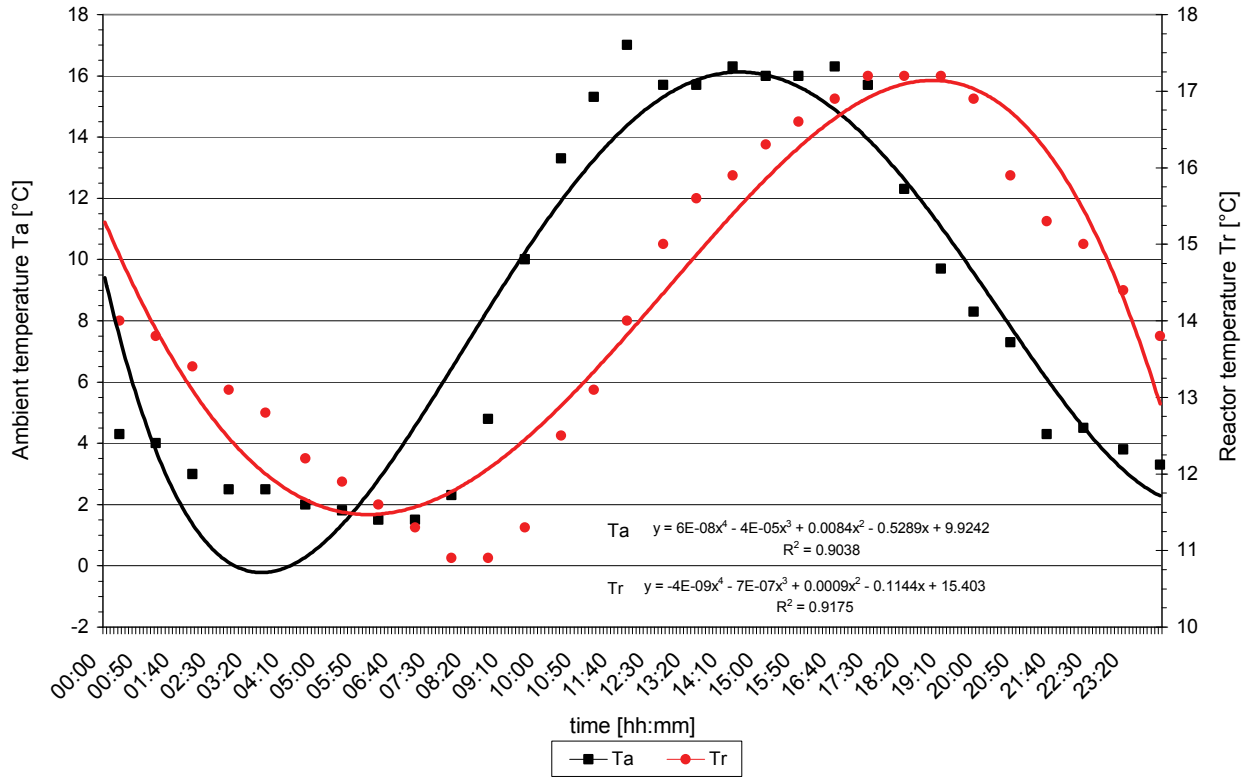


Figure 3-6 Diurnal T_r and T_a profile, plant reactor 1c

3.4 Summary

Long-term T_r variations of about 8°C are recorded from winter to spring. Reactors with surface and bubble aeration at the same plant show T_r differences of more than 5°C, with warm blower air increasing bubble aeration T_r . The increase in T_r in a full-scale plant during a week in spring has been identified at about 4°C, although the diurnal short-term T_r fluctuation of about 1.5°C stays relatively constant. This diurnal T_r variation follows a diurnal T_a variation of 14 to 32°C in spring. The T_a varies from 1 to 17°C in winter at the local plant, leading to an accentuated diurnal T_r fluctuation of about 7.2°C at a small pilot plant. The identified temperature variations at the two sites are summarised as follows:

- Winter surface and diffused aeration systems T_r difference: 5°C,
- Winter to spring surface aeration T_r increase: 8°C,
- Winter T_a fluctuation: minimum of 1°C to maximum of 17°C,
- Spring T_a fluctuation: minimum of 14°C to maximum of 32°C,
- Monthly T_{raw} fluctuation: 4.3°C,

- Weekly T_r (full-scale) fluctuation, spring: minimum of 16.5°C to maximum of 20.5°C,
- Weekly T_r (pilot plant) fluctuation, winter: minimum of 11°C to maximum of 20°C,
- Diurnal T_r (full-scale) fluctuation in a day: 1.5°C,
- Diurnal T_r (pilot plant) fluctuation in a day: 7.2°C, and
- Diurnal T_{raw} fluctuation: <1°C.

Oldham and Rabinowitz (2002) review the application of BNR technology for cold climates in several parts of the world. The key elements in these designs are the BNR responses to low T_r conditions (presumably with surface aeration reactors). Comparable long-term low T_r conditions were identified in this temperature observation study. Reviews of BNR technology in the literature usually exclude MLSS settleability response data to these low T_r conditions.

3.5 Conclusions

The aim of this chapter is to identify operational temperature fluctuations at plant reactors. The following conclusions are based on manual temperature readings and continuous temperature profiles obtained from different reactors at two sites:

- Long-term T_{raw} changes cannot be contributed or directly related to T_a variations,
- Significant seasonal, weekly, and diurnal T_r fluctuations are recorded at plant reactors,
- Significant T_r differences were identified between surface and bubble aeration systems,
- The average T_r changes rapidly over a few days at a full-scale reactor, due to changes in T_a , as well as additional factors,
- The short-term diurnal T_r fluctuation at a full-scale reactor stays constant at 1.5°C during variations, and
- The large T_r fluctuations in a pilot plant reactor demonstrates the direct and rapid influence that meteorological conditions such as T_a has on the MLSS temperature in small containers, as found in pilot plants and test cylinders.

If batch MLSS settling T_s changes significantly from these recorded T_r levels, the batch settling test results and settling parameters will be subject to variations. Batch MLSS settling test results depends on the manner in which T_r is considered during sample handling, before and during MLSS settling tests.

4 BATCH MLSS SETTLING EVALUATION

Batch MLSS settling tests are evaluated in this chapter. The settling results illustrate the effects of temperature variations on aspects of manual batch MLSS settling tests in an operational plant environment.

4.1 Background

The MLSS settling and clarification processes are not evaluated continuously in an operational secondary settling tank (Gernaey *et al.*, 1998). These processes are therefore simulated on laboratory scale in a test cylinder, as represented by the qualitative graphical description in Figure 4-1 (adapted from Kazami and Furumai, 2000).

A MLSS sample from a reactor is placed in a transparent test cylinder to start a batch settling test. The settling liquid to MLSS interface level is recorded for the duration of the settling interval. This settling interval consists of four settling stages: (1) reflocculation, (2) zone settling, (3) transition, and (4) compression (or processes A, C, D, E). The clarification stage (process B) progresses simultaneously on top of the interface.

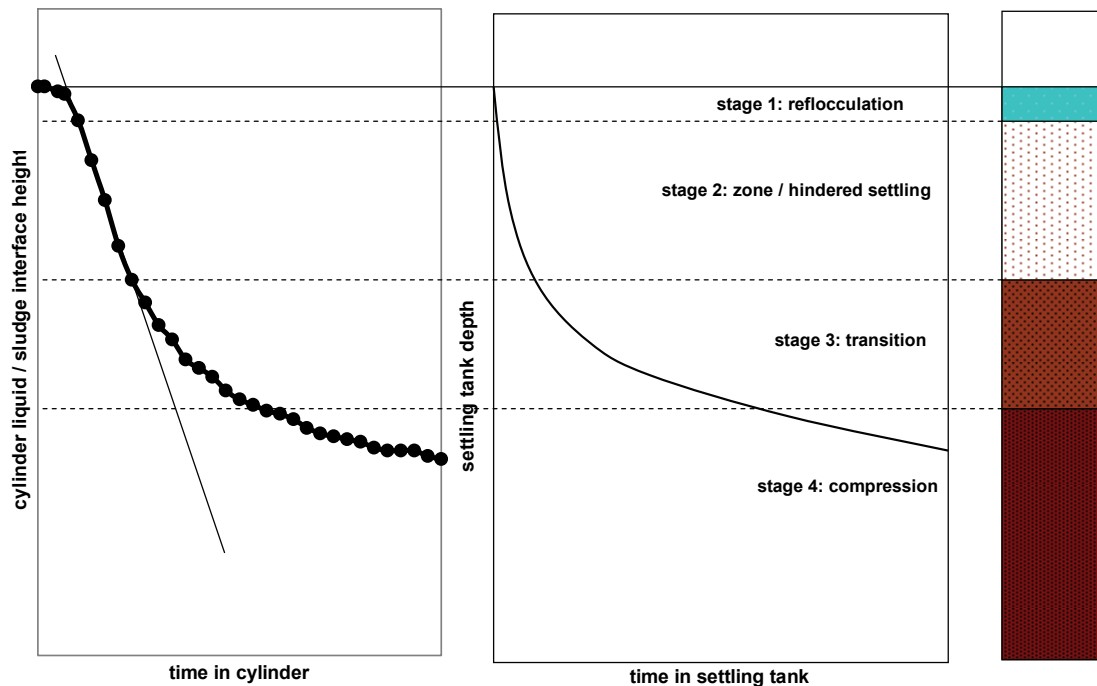


Figure 4-1 MLSS settling in a cylinder and a secondary settling tank

MLSS settling tests are usually performed in a laboratory that is not located near the plant reactor. Therefore, there are time delays between the collection of MLSS samples from the reactor until the start of batch MLSS settling tests. T_s adjusts during collection, transfer, storage, and testing of the MLSS sample towards the prevailing T_a .

The MLSS settling parameter test guidelines (APHA, 1998) are summarised in Table 4-1. The cylinder size, sample stirring provision, and temperature control are the most important experimental conditions that require special equipment. The recommended equipment for SV_{30} and SVI tests are stirred 1 ℓ cylinders that are temperature controlled at T_r . The ZSV test requires larger stirred columns, which must also be temperature controlled at T_r .

Table 4-1 Batch MLSS settling tests procedures (APHA, 1998)

Parameter & method	Container	Temperature control	Stirring	MLSS concentration
SV_{30} , 2710C	1 ℓ transparent cylinder	Yes, at T_r	Yes, < 4 rpm	Not required
SVI, 2710D	1 ℓ transparent cylinder	Yes, at T_r	Yes, < 4 rpm	standard method 2540D
ZSV, 2710E	>1 m high column >10 cm diameter	Yes, at T_r or an evaluation temperature	Yes	Not required

Parker *et al.* (2000) recommend that the purposes of batch MLSS settling tests are identified before experimental methods are finalised. If the test purpose is only preliminary diagnostic work, several relationships are available between ZSV as a function of MLSS concentration and SVI. For more reliable research work to determine ZSV, the standard methods (APHA, 1998) prescribe a long column test with temperature control facilities. Unstirred MLSS settling tests in graduated cylinders are considered as an approximation to determine SV_{30} , SVI, and ZSV. If these test purposes and methods are not considered, MLSS settling tests can lead to the misuse of settling parameters for unsuitable purposes (Dick and Vesilind, 1969), especially when large temperature effects are present.

The aim of this chapter is to use basic batch MLSS settling tests to illustrate how variations in settling parameters obtained from unstirred MLSS settling tests are related to the following aspects:

- settling parameter change in different size test cylinders,
- settling parameter change throughout the three zones of a BNR reactor, and
- settling parameter change during temperature variations.

4.2 Materials and methods

4.2.1 Experimental approach

The extent of MLSS settleability changes at operational temperature ranges, as measured and reported in Chapter 3, is experimentally illustrated. Batch MLSS settling tests determine the impact of three operational test conditions on MLSS settling parameters.

The three test conditions investigated are (i) container size, (ii) BNR reactor zone sample source, and (iii) sample environmental conditions. The settling parameters representing MLSS settleability are SVI, ISV, and supernatant turbidity.

Preliminary tests verify the suitability of a MLSS concentration meter used during temperature variations, the effect of a 1 and 2 ℓ cylinder and the MLSS sample location in a BNR reactor on settling parameters, as well as the impact of extended sample heating and cooling on MLSS settleability.

4.2.2 Settling measurement equipment

Transfer pipettes are used to draw supernatant samples from the cylinders for turbidity measurements. The turbidity measurements are determined with a spectrophotometer (Merck Spectroquant Nova 60; Merck, 2007) calibrated in FNU (Formazine Nephelometric Unit). A hand-held MLSS concentration meter (Royce Model 711) is used for additional MLSS measurements in reactor tanks and batch MLSS samples. The T_s of the MLSS samples in the test cylinders are measured with a hand-held digital thermometer (Testo 925; Testo, 2007). This meter is equipped with a 60 cm immersion probe to detect T_s in the middle of the cylinder.

4.2.3 Settling profile determination

Batch MLSS settling tests are performed in unstirred 2 ℓ graduated cylinders. The four stages of MLSS settling during the 30 minute test, which are (1) reflocculation, (2) zone settling, (3) transition, and (4) compression, are indicated in Figure 4-2 according to profile slope changes (adapted from Ekama *et al.*, 1997). At the start of MLSS settling process, the reflocculation during stage 1 eventually leads to the formation of a liquid to MLSS interface that begins to descend, and a changing profile slope is formed. Once this settling interface reaches maximum settling velocity, the linear portion of the profile indicates zone settling in stage 2. A reduction in settling velocity leads to another change in the profile slope, to indicate transition in stage 3. Compression in stage 4 starts with a more stable slope that continues until the settling test duration is completed, or the liquid to MLSS interface is stationary.

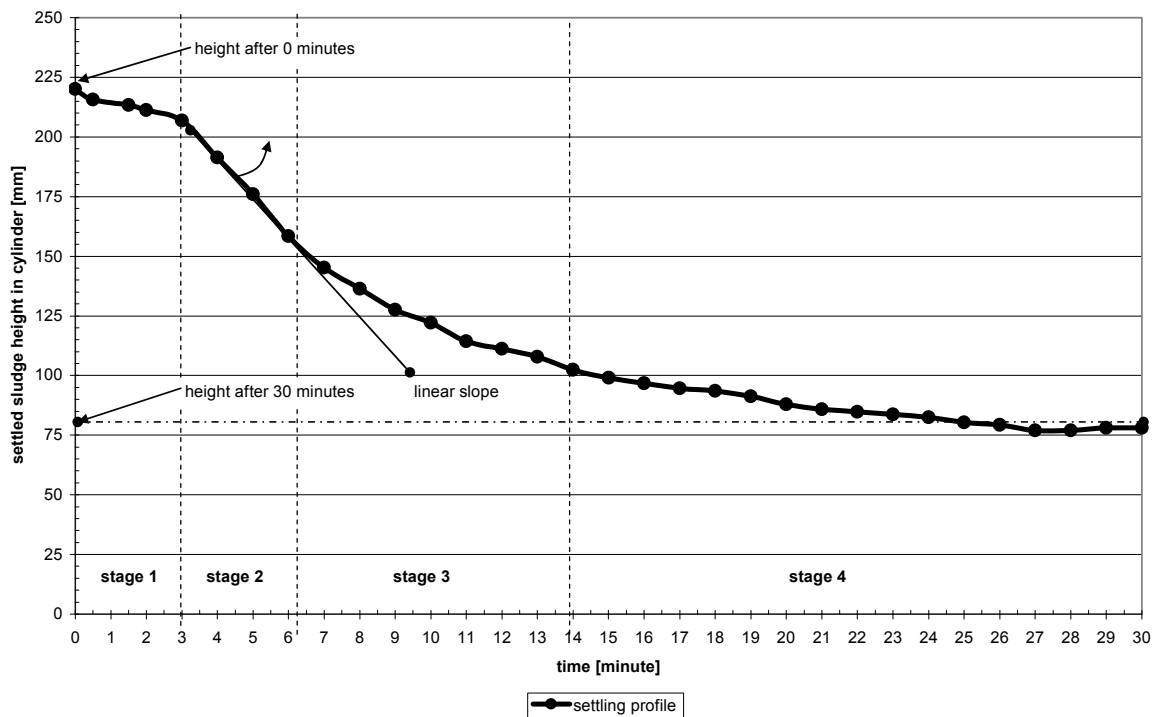


Figure 4-2 Batch MLSS settling profile with 4 settling stages

The ZSV is calculated from the maximum linear slope, and the time to reach ZSV is determined from the start of the linear slope, as indicated in Figure 4-2. SV_{30} is obtained from the height or volume of settled MLSS after 30 minutes, after which SVI is calculated from this SV_{30} and the measured initial MLSS concentration.

4.2.4 Temperature impact on MLSS concentration meter reading

MLSS concentration meter measurements are based on the principle of light scattering caused by the presence of bioflocs (Vanrolleghem *et al.*, 2006). These MLSS concentration meter readings may therefore vary due to the changes in temperature-dependent physical biofloc characteristics. Six MLSS samples in 2 ℓ containers are heated or cooled, and stirred to remix samples, before T_s and MLSS concentrations are measured. The measured MLSS concentrations are plotted against T_s , before the linear curve fitting function of Microsoft Excel is used to identify trends.

In all six tests, the MLSS concentration instrument reading decreases as T_s increases, as summarised in Table 10-14 in Appendix D. The MLSS concentration meter is considered suitable for experimental use within the operational temperature variation range of a few degrees Celsius, as the meter reading change is less than 140 mgSS/ℓ per 10°C T_s change.

4.2.5 Settling container size

MLSS settling results in different sized containers (1 ℓ and 2 ℓ polypropylene graduated cylinders, 20 ℓ plastic drum) are compared to determine if any settling variations are evident over the experimental MLSS concentration range. The dimensions of the graduated cylinders and the plastic drum are listed in Table 4-2. For well-settling MLSS, even a small 1 ℓ cylinder with a narrow diameter (about 60 mm), should not cause any cylinder wall effects on settling (Bhargava and Rajagopal, 1993).

Table 4-2 Batch settling tests container size

Container	Length and Width [mm]	Diameter [mm]	Height [mm]
1 ℓ	N/A	60.0	355
2 ℓ	N/A	76.8	432
20 ℓ	210 and 250	N/A	405

4.2.6 Reactor zone samples

Thirty-five sets of 2 ℓ grab MLSS samples are periodically taken from the anaerobic zone and anoxic zone, as well as four of the six aerobic zone sections (1 and 2 from start, 3 and 4 from end) of a pilot plant BNR reactor (refer to Appendix A1 for plant description).

MLSS concentration and DO concentration, as well as T_r , are measured in these reactor zones. Batch MLSS settling tests are performed and settling profiles are tabulated. Clarified supernatant samples are collected to measure the turbidity. The SV_{30} is obtained from the settling profile to calculate the SVI. The ISV is then calculated from the settled MLSS height difference over the period of 2 to 5 minutes.

The pilot plant reactor zone conditions, as summarised in Table 10-15 in Appendix E, indicate relatively stable process conditions. The DO concentrations of the anaerobic and anoxic zones are low (below 0.1 mg/l), while the DO concentrations are above 2.0 mg/l in most of the aerobic zones. The MLSS concentration is an average of about 3500 mg/l, with a standard variation of less than 300 mg/l. The MLSS sample settling tests are usually performed late morning or early afternoon at similar climatic conditions, which is reflected in the low standard deviation in reactor zone temperatures. The higher temperature of about 1°C in the aerobic zone 1 is due to the temporary installation of a heater probe in an attempt to control the T_r of the pilot plant reactor.

4.2.7 Additional preliminary tests: extended heating and cooling

Preliminary extended heating and cooling test results are summarised in Table 10-16 in Appendix E. The results indicate that MLSS settling changes due to temperature variations are not linear. Larger settleability changes are evident at lower temperatures.

Several studies (Çetin and Sürücü, 1990; Krishna and Van Loosdrecht, 1999; Morgan-Sagastume and Allen, 2003; Zhang *et al.*, 2006b) reported poorer MLSS settling at elevated temperatures. SVI values increased (up to 540 ml/g) at long-term elevated temperatures as high as 35 to 45°C. These extreme temperature conditions resulted in deflocculation and reduced MLSS settling properties, as confirmed experimentally by Wilén *et al.* (2006) at 30 to 45°C, as well as at 4°C. Some of these MLSS settling studies were performed at industrial wastewater plants, as well as during long-term temperature variations. These observations illustrate the importance of proper reference conditions during MLSS settling evaluations. Empirical settling models are not valid outside experimental temperature boundaries. This preliminary test confirmed that MLSS settleability is not directly related to temperature variations outside these experimental boundaries.

4.2.8 Sample conditioning methods

To change the environmental conditions, 1 ℓ and 2 ℓ cylinders are placed in direct sunlight or in shade. The rest of the experimental method is identical to previous procedures.

4.3 Results and discussion

4.3.1 Impact of container size on MLSS settling

The container size does not play a significant role in settling of MLSS samples, when judged by the average variation in settling parameters listed in Table 4-3. The raw experimental data is tabulated in Table 10-17 and trends are displayed in Figure 10-39 to Figure 10-50 in Appendix E. For the average MLSS concentration of 4203 mg/ℓ, the average SVI, ISV, and supernatant turbidity from the three settling tests for the 1 ℓ and 2 ℓ cylinders differ by 4 mℓ/g, 0.14 m/hr, and 2 FNU respectively. The smaller 1 ℓ cylinder samples heated up slightly faster, due to solar radiation, during the 30 minute settling tests. The faster sample heating in the 1 ℓ cylinder resulted after 30 minutes (T_{s30}) in a small T_s difference of 0.3°C between the 1 ℓ and 2 ℓ cylinder samples.

Table 4-3 Impact of container size on MLSS settling

Container [ℓ]	T_{s30} [°C]	SVI [mℓ/g]	ISV [m/hr]	Turbidity [FNU]
1	23.5	108	0.70	19
2	23.2	111	0.84	21
20	20.6	126	0.64	15

The settling results of the 20 ℓ sample differ slightly from the 1 ℓ and 2 ℓ samples. The limited area exposed to solar radiation in the 20 ℓ container causes a slower T_s increase, compared to the 1 ℓ and 2 ℓ cylinders. At the lower T_s in the 20 ℓ container, the SVI is slightly higher and the ISV and supernatant turbidity slightly lower. The SVI, ISV, and turbidity change in the 20 ℓ container points directly towards the significant T_s change impact on MLSS settleability. Wall effects and biofloc bridging effects are not present in the large 20 ℓ container. The reduced settleability (in terms of SVI and ISV) of the 20 ℓ sample is therefore related to T_s differences between small and large containers.

The SVI, ISV, and supernatant turbidity variations in the 1 ℓ, 2 ℓ, and 20 ℓ containers are small enough to accept that the 2 ℓ cylinder is suitable for the MLSS settling evaluations scheduled in the rest of the experimental work. This verification ensures the container size is not a factor in 2 ℓ batch settling and 2 ℓ on-line settling tests (based on the use of well-settling MLSS samples).

4.3.2 Impact of reactor zone on MLSS settling

Settling parameters are influenced differently as the MLSS moves through the three reactor zones. The SVI, ISV, and supernatant turbidity data is summarised in Table 10-15 in Appendix E, and illustrated in Figure 4-3. The SVI improves slightly after entering the aerobic reactor zone, but the ISV in essence stays unchanged through the three reactor zones. Supernatant turbidity reduces noticeably throughout the three reactor zones. This leads to a MLSS clarification improvement through successive zones in the BNR reactor.

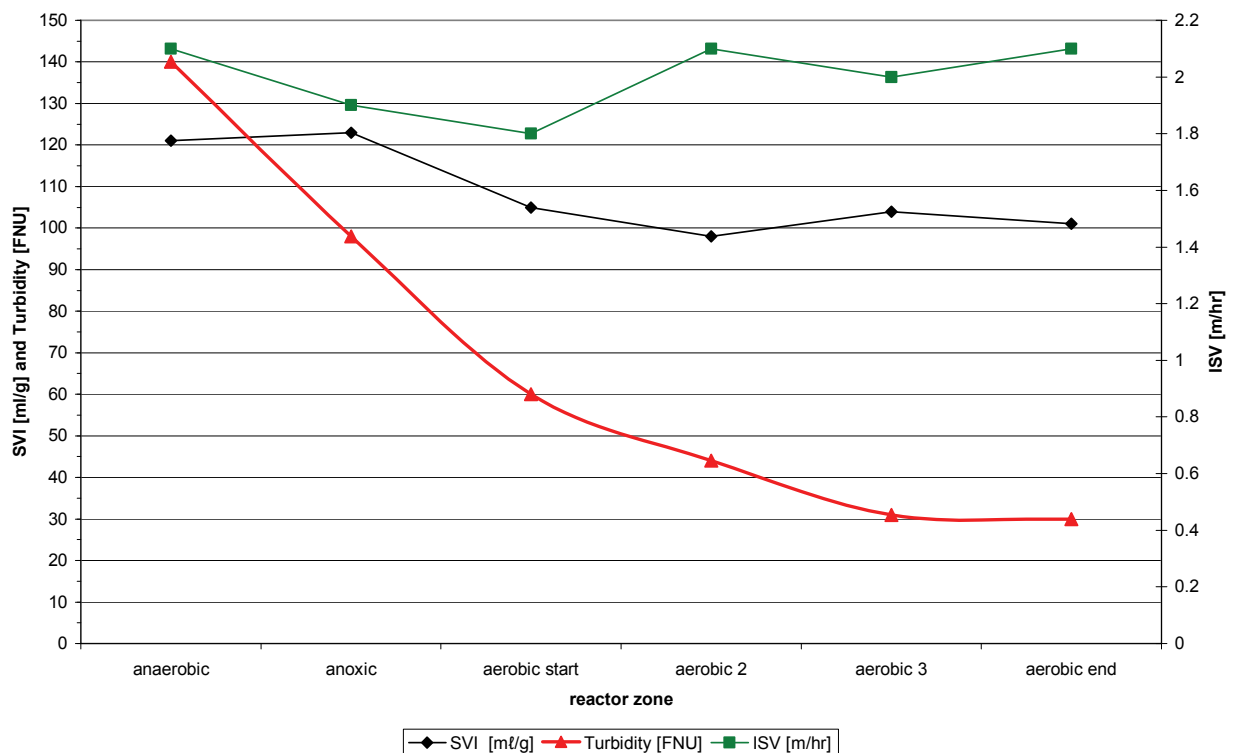


Figure 4-3 Settling parameters changes throughout three BNR reactor zones

The SVI improves from an average of 122 ml/g from the non-aerated anaerobic to anoxic zones, to an average of 102 ml/g in the four aerobic zones. The first aerobic section MLSS has a slightly higher SVI of 105 ml/g, against the average of 101 ml/g for the MLSS in the other three aerobic sections. There is an immediate SVI improvement from

the unaerated anoxic zone to the first aerobic zone. The standard deviation of SVI of 31 mL/g in the anaerobic to anoxic zones reduces to 11 mL/g in the four sections of the aerobic zone, which indicates a more stable SVI under aeration. The shift, from unaerated to aerated conditions, results in a small improvement in SVI, with an average SVI reduction measured at 19 mL/g.

ISV stays constant at an average of 2.0 m/hr from the anaerobic to anoxic zones, to 2.0 m/hr in the four sections of the aerobic zone. The average standard deviation of 0.6 m/hr stays constant throughout the reactor zones, for comparable settling velocity conditions in all reactor zones. The shift from unaerated to aerated conditions does not change the ISV significantly, with changes of about 0.3 m/hr measured between adjacent reactor zones.

Settled sewage mixes with RAS to create an anaerobic zone at the reactor inlet, forming a MLSS with the highest supernatant turbidity of 140 FNU. This turbidity decreases by 42 FNU to 98 FNU in the anoxic zone, as the zone retention time and aerated a-recycle MLSS introduced into the anoxic zone appears to assist with MLSS flocculation to reduce supernatant turbidity. The turbidity reduces then by 38 FNU to 60 FNU in the first section of the aerobic zone. The turbidity reduction from the anaerobic zone to the start of the aerobic zone is 69%. The turbidity reduces subsequently slightly by 16 and 13 FNU in the second and third section of the aerobic zone, to 44 and 31 FNU respectively. No additional turbidity reduction is detected in the last section of the aerobic zone.

It appears that once a minimum aeration period is reached, extended aeration is not beneficial for further supernatant turbidity improvement. These results illustrate hydraulic residence time requirements in reactors and settling tanks, as simulated for MLSS settling by the 30-minute settling test duration. Ekama *et al.* (1997) found that a 1200 second (20 minute) flocculation duration is sufficient in full-scale settling tanks. The simulated 30-minute MLSS settling test is thus appropriate to determine the extent of supernatant clarification.

MLSS deflocculates when exposed to anaerobic conditions (Wilén *et al.*, 2000), as found in the anaerobic reactor zone. Reflocculation occurs relatively fast in the aerobic reactor zone or under quiescent conditions in the stilling chamber of a secondary settling tank. The SVI or settling velocity changes due to temperature variations in the different reactor

zones is unknown from the available literature. This preliminary survey with 35 MLSS samples from six sections of a BNR reactor indicated the following changes to three MLSS settling parameters:

- SVI improves slightly in aerobic reactor,
- ISV is relatively constant throughout reactor zones, and
- Supernatant turbidity reduces throughout BNR reactor zones.

4.3.3 Impact of container environment on MLSS settling

MLSS settling curves represent individual plant reactor conditions, and settling characteristics of MLSS is accordingly unique (Stypka, 1998). MLSS settling models, such as the Takács model (Takács *et al.*, 1991), require calibration with site-specific MLSS settling characteristics (Wilén, 2006).

The container environment plays a significant role in MLSS settling over an average MLSS concentration range of 4203 mg/ℓ, as summarised in Table 4-4. The raw data is tabulated in Table 10-17 in Appendix E, and trends are displayed in Figure 10-39 to Figure 10-50 in Appendix E. The average SVI, ISV, and supernatant turbidity over three tests with the 1 ℓ and 2 ℓ cylinders differ significantly by about 50%, due to the placement of the cylinders in the sun or shade.

Table 4-4 Impact of container environment temperature on settling (T_r 19.6°C, T_a 17.9°C)

Cylinder [ℓ]	Position	T [°C] after 30 min	SVI [mℓ/g]	Change [mℓ/g/1°C]	ISV [m/hr]	change [m/hr/1°C]	Turbidity [FNU]	change [FNU/1°C]
1	Sun	23.5	108	N/A	0.70	N/A	19	N/A
	Shade	19.1	174	-15	0.04	0.15	14	1.2
2	Sun	23.2	111	N/A	0.84	N/A	21	N/A
	Shade	19.1	171	-14.6	0.44	0.10	14	1.7

SVI decreases with the 1 ℓ sample and 2 ℓ sample is 15.0 mℓ/g and 14.6 mℓ/g per 1°C T_s increase respectively. The corresponding ISV increase is 0.15 m/hr and 0.10 m/hr per 1°C T_s increase respectively. The corresponding supernatant turbidity increase is 1.2 FNU and

1.7 FNU per 1°C T_s increase respectively. The average SVI decrease, ISV increase, and supernatant turbidity increase are therefore 14.8 mL/g, 0.12 m/hr, and 1.42 FNU per 1°C T_s increase respectively.

Local effects of solar radiation on sample placements in the shade or direct sunlight result in a temperature difference of about 4.3°C over 30 minutes. This large T_s variation confirms the important effect of solar radiation intensity on water bodies, as observed by Tadesse *et al.* (2004). These large variations (in excess of 50%) in SVI, ISV, and supernatant turbidity, indicate the importance of sample environmental conditions, as well as temperature measurements and recording, before and during batch MLSS settling tests.

4.4 Summary

Several aspects of batch MLSS settling tests procedures could influence results. The only three aspects of settling procedures evaluated consist of (i) container size, (ii) reactor zone sample origin, and (iii) container environment.

- Container size (1 ℓ, 2 ℓ or 20 ℓ) does not change the SVI, ISV, or supernatant turbidity of the plant specific MLSS samples significantly.
- MLSS samples from the three BNR reactor zones do not exhibit large variations in SVI or ISV, but the clarified supernatant turbidity improves throughout successive BNR reactor zones.
- Temperature dependent MLSS settling variations are not linear over an extended T_s range. A larger MLSS settleability deterioration change is evident at the lower T_s .
- Temperature variations during sample handling have significant impacts on MLSS settling. An average SVI decrease of 14.8 mL/g per 1°C T_s increase, an ISV increase of 0.12 m/hr per 1°C T_s increase, combined with a supernatant turbidity increase of 1.7 FNU per 1°C T_s increase, were measured during 30-minute MLSS batch settling tests, at a T_s variation range of about 4.3°C.

- No temperature dependency trends are identified across the BNR reactor from these standard MLSS batch settling tests. This indicates the insensitivity of conventional settling equipment and methods to perform temperature dependent batch MLSS settling tests over small operational T_r ranges.

4.5 Conclusions

The general conclusions to summarise experimental results are as follows:

- Temperature has a significant impact on MLSS settling, with a SVI decrease of 14.8 ml/g per 1°C T_s increase, an ISV increase of 0.12 m/hr per 1°C T_s increase, combined with a clarified supernatant turbidity increase of 1.7 FNU per 1°C T_s increase. At higher temperatures within the operational T_s range, MLSS settling improves, and supernatant clarification deteriorates.
- Temperature dependent MLSS settling variations are not linear, with larger MLSS settleability deterioration changes evident at lower temperatures, when compared to small MLSS settleability changes at higher temperatures outside the operational T_s range.
- There is an immediate, but relatively small, improvement in MLSS settleability, in terms of SVI, when anaerobic MLSS is aerated.
- There is a continuous improvement in supernatant clarification, according to the turbidity reduction, when anaerobic MLSS transfers through successive reactor zones. Aeration results in supernatant turbidity reduction until a minimum turbidity is reached
- Existing conventional batch settling equipment and traditional basic procedures are not suitable to effortlessly identify temperature dependent MLSS settling changes over small operational T_r ranges.

The significant effects of short-term temperature changes on batch MLSS settling test results creates the need for more advanced MLSS settling monitoring techniques. On-line MLSS settling is such a technique, where temperature compensation is incorporated in the sampling and settling test method.

5 ON-LINE MLSS SETTLING EVALUATION

On-line MLSS settling profiles are evaluated in this chapter. Profiles are obtained from an automated MLSS settling meter used at a full-scale plant to calculate temperature-based settling parameters. The improved MLSS settling models illustrate the effects of including diurnal temperature fluctuations in the determination of settling parameters.

5.1 Background

The capacity and performance of a secondary settling tank relates to the velocity at which MLSS separates and settles to the bottom of the tank (Jeyanayagam *et al.*, 2006). MLSS concentration and MLSS settling velocity measurements are thus required to perform a batch MLSS settleability evaluation. On-line instrumentation is available to perform these manual measurements on an automated basis. Gernaey *et al.* (1998) consider the development and use of such on-line MLSS settling meters as a major improvement on batch MLSS settleability tests.

MLSS concentration is the main factor that contributes to variations in the MLSS settling process (Reardon, 2005). Numerous additional settleability factors are summarised for reference purposes in alphabetical order in Table 10-19 to Table 10-24 in Appendix G. These factors create suitable conditions for the formation of a well-settling MLSS. The most essential factors include a sufficient sludge age in the BNR reactor, combined with suitable DO concentrations in the different reactor zones, as well as a wastewater feed containing adequate substrates (De Clercq *et al.*, 2007).

Temperature is a settleability factor that affects several aspects of MLSS settling (Morgan-Sagastume and Allen, 2003). Temperature modifies water density and water viscosity (Clements, 1976), as well as the surface and composition characteristics of the individual bioflocs (Gerardi, 2002). These temperature-based MLSS settling changes are highly variable, due to operational T_r variations. The short-term T_r variations follow diurnal T_a fluctuations, while long-term T_r variations follow seasonal T_a fluctuations (Wahlberg *et al.*, 1996).

On-line MLSS settling meters are ideally suited to monitor and collect MLSS settling data over these diurnal T_r fluctuations. Three main developments represent the implementation of automated MLSS settling equipment. (i) One of the first reported MLSS settling meters was developed in Japan (Sekine *et al.*, 1989) in the late 1980s for batch settling tests. This MLSS settling meter is able to measure SVI, compression velocity, as well as ISV. (ii) A second unit was developed in Belgium (Vanderhasselt *et al.*, 1999b) in the 1990s for on-line MLSS settling tests. This settling meter includes a stirrer to measure SSVI. Vanrolleghem *et al.* (1996) reports that this meter is designed with a sample dilution function to measure DSVI. (iii) Wahlberg (2004) reported on the development of a third settling meter in the USA. This meter is patented as an apparatus, as well as an integrated method, to measure and manipulate MLSS settling, compression and flocculating characteristics.

Simon *et al.* (2005) and Lynnggaard-Jensen and Lading (2006) recently described a novel settling meter sensor that consists of a sample chamber intended for direct submersion into a reactor. This sensor is equipped with an array camera and photo sensor to measure the MLSS settling interface over 30 minutes. These reports indicate that substantial research and development is directed to automate aspects of the traditional batch MLSS settling test.

The aim of this chapter is to model temperature dependent MLSS settling parameters. The parameters are obtained from semi-continuous MLSS settling profiles that are generated during diurnal T_r fluctuations with the use of an automated on-line MLSS settling meter.

5.2 Materials and methods

5.2.1 Experimental approach

On-line MLSS settling tests are performed at a full-scale BNR plant reactor outlet. Van Huyssteen *et al.* (1990) describe this plant in some detail. These settling tests are required to confirm that the range of temperature related full-scale MLSS settling changes are comparable to settling changes identified during batch MLSS settling tests in Chapter 4.

The automated on-line MLSS settling meter generates about 40 successive MLSS settling profiles per 24-hour day. The settling data and profiles, in electronic format, are used to

calculate settling parameters. A statistical computer software program evaluates these parameter correlations to obtain temperature dependent MLSS settling models. A practical procedure is therefore provided to improve the reliability of MLSS settling parameters, as effects of short-term temperature variations before and during MLSS settling tests can be reduced.

5.2.2 MLSS settling meter configuration

The custom-built MLSS settling meter automates the monitoring and recording of batch MLSS settling tests. The settling meter monitoring method is based on a vertical moving single point infrared light detector that consists of a light source and receiver. The light detector follows the descending liquid to MLSS interface along a transparent cylinder filled with MLSS. The program logic controller (PLC) records the height of the light detector in electronic format during the MLSS settling period, thereby generating a settling profile.

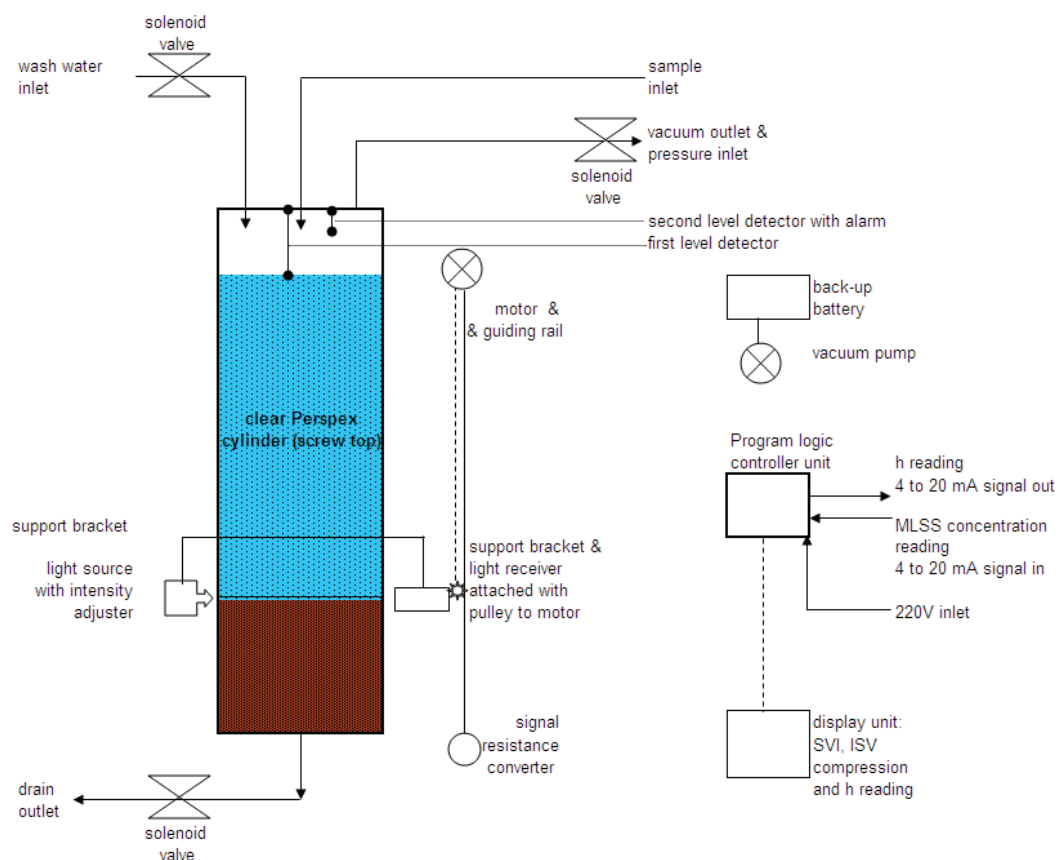


Figure 5-1 Schematic diagram of main components of the MLSS settling meter

Three requirements of the MLSS settling meter are: (i) to obtain MLSS samples for tests without subjecting bioflocs to excessive turbulence, (ii) to trend successive 30-minute MLSS settling profiles together with T_r and MLSS concentration data, and (iii) to operate fully automated and without supervision.

Figure 5-1 illustrates the main components of the MLSS settling meter. A vacuum driven sample suction system transfers the MLSS sample from the reactor basin into the cylinder. The vacuum system also pressurises the cylinder after each settling test to drain the cylinder, and to flush out any stagnant MLSS sample trapped in the transfer pipe. The vacuum system ensures the MLSS sample is not exposed to excessive pump shear during sample transfer. A wide cylinder is used to prevent or reduce wall effects during settling. The clear Perspex cylinder has a working volume of 2 ℓ, with a height of 360.9 mm, an internal diameter of 84.0 mm, and a wall thickness of 3.5 mm.

The MLSS sample transfer is rapid and the cylinder fills up within a few seconds. The MLSS sample discharge into the cylinder creates enough turbulence to ensure the sample mixes homogeneously. The settling test starts immediately after a cylinder level detector stops the sample transfer. The scanner moves downward to follow the settling liquid to MLSS interface level during the 30-minute test duration. The light sensor activates almost instantaneously as the MLSS settles, due to the scanner light source signal that the detector receives through the transparent clarified supernatant. The sensor stops moving down once the scanner light source signal is lost, due to the opaque settled MLSS. The sensor moves downward in about 4 mm increments, which is the minimum distance that the geared drive unit of the sensor can move.

The PLC records the MLSS interface level after each minute of the 30 minutes settling period. The PLC calculates the initial settling velocity (minutes 2 to 5 of the 30 minutes test) and the SVI. These parameter values appear on a digital display unit after each settling cycle. The settling meter has a manual termination function to cancel a test and to restart the complete settling cycle.

The settling meter is relatively mobile and simple to commission. The meter start-up requires a 220 V power source, a potable wash water supply, a 4 to 20 mA signal input from the reactor MLSS concentration meter, as well as a MLSS sample source. The

MLSS concentration reading is not essential for the MLSS settling meter operation, as it is only used for the SVI display and SVI calculation. The settling meter and components are installed in a fully enclosed weatherproof cabinet, to eliminate or reduce meteorological effects, such as wind, rain, solar radiation, and T_a changes. The automated operation sequence to create one MLSS settling profile consists of the following three steps:

Step 1: MLSS sample preparation

- cylinder drain valve opens,
- cylinder chamber pressurises to force out previous MLSS sample through bottom drain and to flush top MLSS sample inlet line, adjustable duration of 5 seconds,
- potable wash water cleaning cycle to spray inner cylinder walls, adjustable duration 4 seconds,
- cylinder chamber pressurises to force out wash water through bottom drain, adjustable duration 5 seconds,
- cylinder drain valve closes,
- cylinder chamber under vacuum to extract MLSS sample from reactor basin into cylinder,
- vacuum stops when cylinder maximum level sensor at 2 ℓ capacity is detected,
- external initial reactor MLSS concentration reading obtained for SVI calculation, and
- external logger T_r is recorded.

Step 2: MLSS settling test

- 30 minute counter starts,
- MLSS settling interface height is recorded every minute for 30 minutes according to level of light detector,
- height reading capture at 120 seconds,
- height reading capture at 300 seconds, calculate and display ISV (2 to 5 minutes),
- height reading capture at 1500 seconds,
- height reading capture at 1790 seconds, calculate and display compression velocity (25 to 30 minutes), and

- final height capture according to light detector level at 30 minutes, calculate and display SVI.

Step 3: MLSS sample removal

- light detector moves upwards to the start position at maximum cylinder height level, and
- step 1 restarts after a total of 46 minutes (16-minute adjustable period between tests), except if the manual override function is turned on at any stage to return to start of step 1.

A two-channel data logger (Microlog Plus; Fourier, 2007) captures the settling meter height profiles. The logger data is recorded in a Microsoft Excel compatible format for manual download to a computer.

5.2.3 MLSS settling meter velocity data collection method

The settled MLSS height (h) variations over 30 minutes settling tests are obtained from the original MLSS settling profiles, as illustrated in Figure 5-2. The stage 1 lag time, stage 2 ZSV, stage 3 transition, and stage 4 compression are indicated on successive settling profiles.

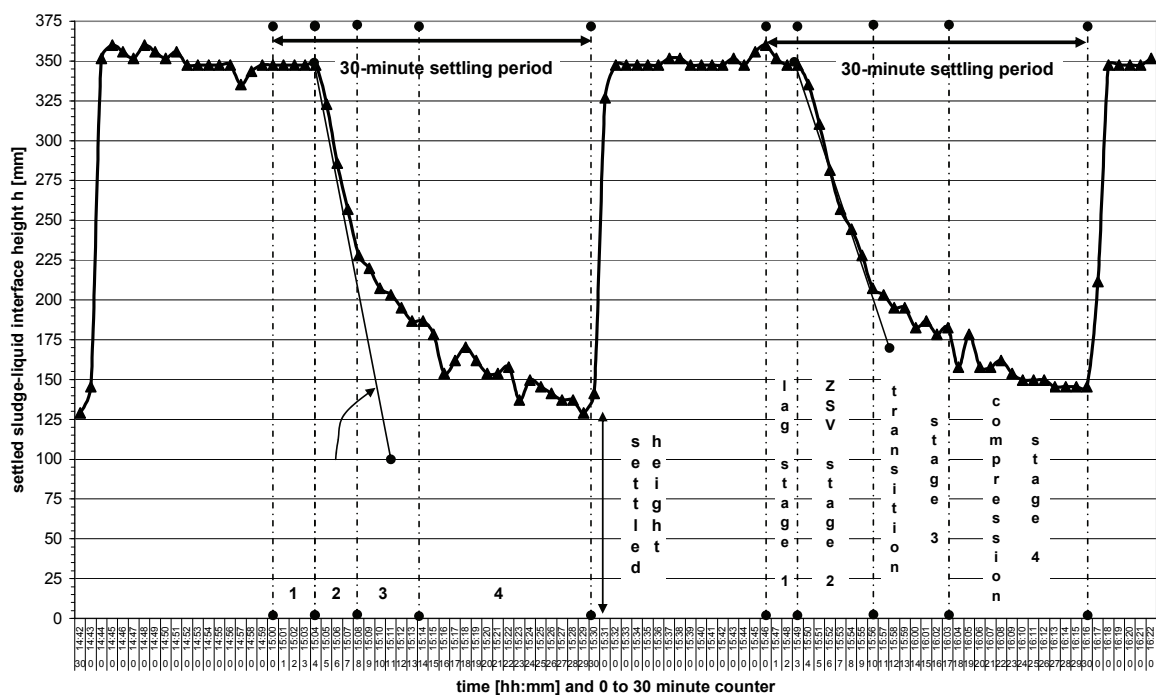


Figure 5-2 Two consecutive on-line MLSS settling profiles recorded by the settling meter

The MLSS settling parameters are computed from these settling profiles with the use of a Microsoft Excel spreadsheet as follows:

- lag time before settling of liquid to MLSS interface starts (stage 1),
- ISV from period 2 to 5 minutes of MLSS settling,
- $u_{\max}$ from the linear negative slope (stage 2),
- $t_{\max}$ from the moment when $u_{\max}$ commences (start of stage 2),
- SV_{30} from the settled MLSS height after 30 minutes (end of stage 4), and
- incremental average 5-minute MLSS settling velocities over 30 minutes: u_1 , u_2 , u_3 , u_4 , u_5 , u_6 .

5.2.4 MLSS settling meter velocity data collection boundaries

The on-line MLSS meter generated 85 settling profiles for the full-scale plant. The experimental data range boundaries for these profiles are listed in Table 5-1. The MLSS concentration and T_r variations at the full-scale plant are recorded from 4489 to 4923 mgSS/ℓ, and from 17.2 to 19.0°C respectively.

Table 5-1 Experimental data range for on-line MLSS settling evaluation

Parameter	Full-scale reactor condition
n	85
Minimum T_r [°C]	17.2
Maximum T_r [°C]	19.0
Minimum MLSS concentration [mg/ℓ]	4489
Maximum MLSS concentration [mg/ℓ]	4923

5.2.5 Data presentation

5.2.5.1 Data logger transfer and calculations

A data logger (Microlog Plus; Fourier, 2007) equipped with an internal thermometer measures and records T_r . The logger has an external 4 to 20 mA signal input facility that is used to store the settling meter h data. A similar data logger is used to record T_r from the built-in thermometer of the DO concentration meter (ATI Model B15\60; ATI, 2007). An additional data logger (Alog MCS131LCD; MC Systems, 2007) stores the on-line

data from the DO and MLSS concentration meters. The data collection proceeds as follows:

- The DO concentration meter data logger produces a data table of readings of date [dd-mm-yyyy], time [hh:mm] in 5 minute increments, and DO concentration [mg/l] in 0.1 mg/l increments. The data tables are transferred into Excel spreadsheets.
- The MLSS concentration meter data logger produces a data table of readings of date [dd-mm-yyyy], time [hh:mm] in 5 minute increments, and MLSS concentration [mg/l] in 0.1 mg/l increments. The data tables are transferred into Excel spreadsheets.
- The MLSS settling meter data logger produces a data table of readings of date [dd-mm-yyyy], time [hh:mm:ss] in 1 minute increments, and height [mm] in 0.1 mm increments. The data tables are transferred into Excel spreadsheets.
- The thermometers data produces data tables of readings of date [dd-mm-yyyy], time [hh:mm] in 5 minute increments, T_a from the internal ambient temperature sensor in 0.3°C increments and T_r from the DO concentration meter temperature sensor [°C] in 0.3°C increments. The data tables are transferred into Excel spreadsheets.

The Excel spreadsheet containing the settling meter height data is the reference sheet for all calculations. An example of a settling data graph is provided in Figure 10-51 in Appendix F. Data in the spreadsheet is not filtered to remove noise. Bergh (1996) describes experimental noise as fluctuations in measurements that originate from the process or measuring devices used.

The cylinder height readings [mm] are converted to cylinder volume values [mℓ], by using the diameter value of 0.084 m to calculate height from a cylinder area of 0.0055 m². The DO concentration and T_r readings are averaged over each 30 minute settling period, and the initial MLSS concentration reading is used to calculate SVI. The MLSS settling profile over 30 minutes is used to calculate the 11 MLSS settling parameters: SVI [mℓ/g], SV_{30} [mℓ], u_{max} [m/hr], u_{ave} [m/hr], t_{umax} [minute], and the six incremental u_1 to u_6 five-minute settling velocities [m/hr].

The reference Microsoft Excel spreadsheet is used to list the date, time, DO concentration, MLSS concentration, SV_{30} , SVI, t_{umax} , u_{max} , u_{ave} , and u_1 to u_6 . The two dependent variables, MLSS concentration and T_r , are transferred together with the 11 settling parameters into the DataFit (2005) statistical computer program.

5.2.5.2 Empirical settling correlations and statistical comparisons

The MLSS settling data is used to generate 2-D best-fit correlations between the MLSS concentration and the 11 MLSS settling parameters. The same settling data is then used to generate 3-D best-fit correlations with MLSS concentration, T_r , and the 11 MLSS settling parameters. To evaluate the impact of T_r inclusion, the improvement in correlations can be statistically determined by comparing R^2 values. R^2 is the most widespread coefficient to assess MLSS settling models (Ozinsky and Ekama, 1995).

There are 298 single independent 2-D regression models and 242 3-D non-linear regression models pre-defined in DataFit. These pre-defined models allocate best-fit correlations for the settling data according to R^2 -values. This automatic ranking function of DataFit identifies the best-fit correlations.

The DataFit package generates 3-D plots of the regression models, where the dependent variables are allocated to the x_1 - and x_2 -axes, and the response variables to the y-axis. In the graphical display of the non-linear regressions, bullets above and below the surfaces indicate the data points, and the surfaces with colour bands indicate the regression result ranges. The built-in regression analysis function of Microsoft Excel analyzes the rest of the experimental MLSS settling data.

5.3 Results and discussion

The mathematical relationships between settleability parameters are approximated as basic polynomial functions, to show trends that adequately describe MLSS settling behaviour. The on-line MLSS settling results are presented in the following sections:

- settling parameters diurnal profiles (h, MLSS concentration, SVI)
- settling parameters best-fit model
 - ▣ dependent variables: MLSS concentration and T_r
 - ▣ response variables: SVI, u_{max} , and t_{umax}
- settling parameter model correlations (SVI with u_{max} and t_{umax})
- settling parameters simplified models
 - ▣ dependent variables: MLSS concentration and T_r
 - ▣ response variables: SVI, u_{max} , t_{umax} , u_{ave} , h, u_1 , u_2 , u_3 , u_4 , u_5 , u_6

5.3.1 T_r and h diurnal variation

The recorded data points and fitted trends for the diurnal T_r and settled MLSS height variations are shown in Figure 5-3. The x_1 -axis indicates the 24-hour diurnal period, the primary y_1 -axis indicates T_r , and the secondary y_2 -axis indicates the on-line MLSS settling meter h reading.

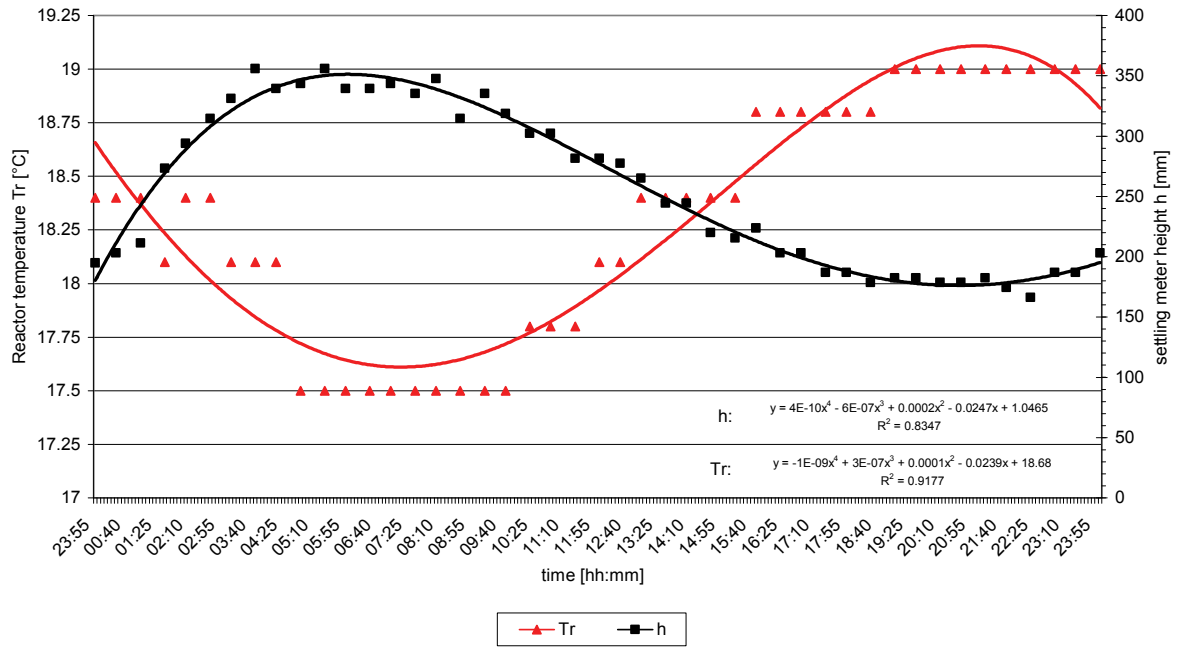


Figure 5-3 Data and fitted curves of temporal variations in T_r and h

The full-scale plant T_r fluctuated by about 1.5°C per day in spring. The T_r profile changed from 17.5 to 19.0°C, and the h profile changed from about 350 to 170 mm, as shown in Figure 5-3. The T_r and h profiles follow sinusoidal trends, as represented by the fitted curves with R^2 of 0.92 and 0.83 respectively. From the on-line MLSS settling tests, the MLSS settling meter height reading illustrated the inverse relationship between T_r and the 30-minute settled MLSS height in a settling test cylinder.

5.3.2 MLSS concentration and T_r diurnal variation

The recorded data points and fitted trends for the diurnal T_r and MLSS concentration variations for the full-scale plant are shown in Figure 5-4. The x_1 -axis indicates the 24-hour diurnal period, the primary y_1 -axis indicates T_r and the secondary y_2 -axis indicates the on-line MLSS concentration reading. Two 2-day profiles, with T_r and MLSS concentration correlations R^2 of 0.91 and 0.90 respectively, is provided in Figure 10-53 in Appendix F for reference purposes.

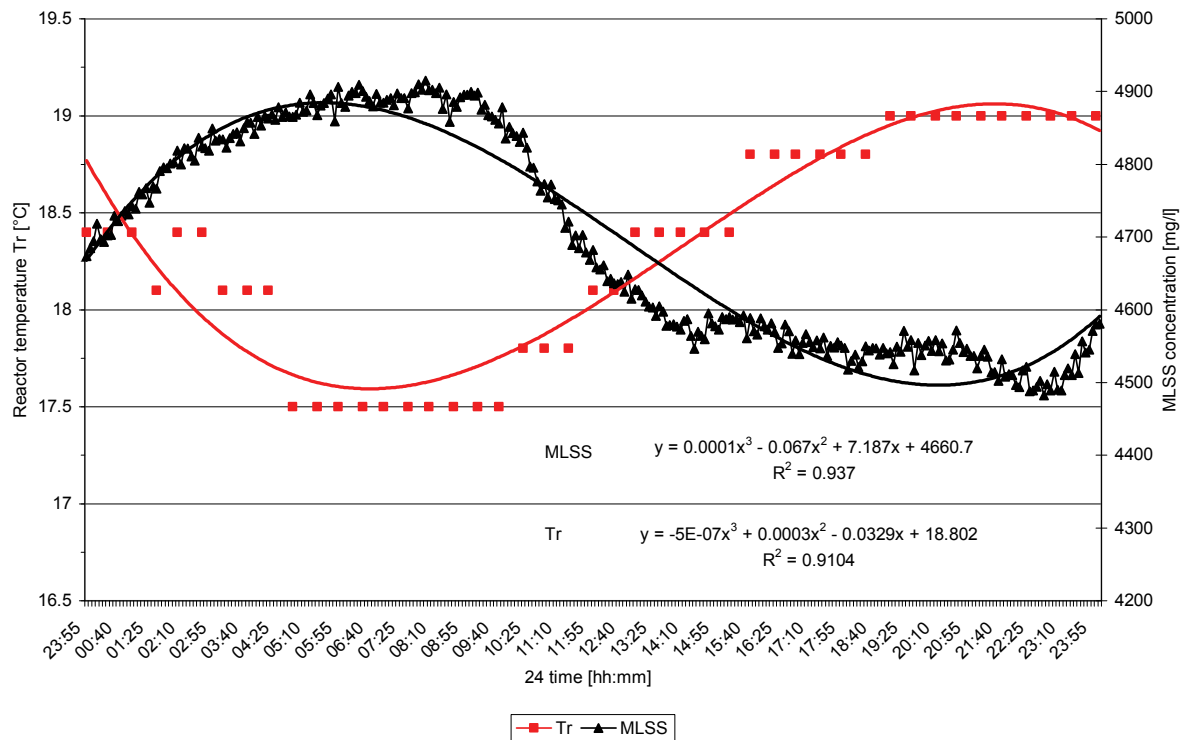


Figure 5-4 Data and fitted curves of temporal variations in T_r and MLSS concentration

The full-scale plant average MLSS concentration varies by about 400 mg/ℓ per day. The diurnal MLSS loading variations, originating from the plant and reactor inflow, as well as the secondary settling tank RAS flow, cause the MLSS concentration variations (Otterpohl and Freund, 1992). The MLSS concentration profile was relatively smooth over the 24-hour period, as shown in Figure 5-4. The T_r and MLSS concentration profiles follow a sinusoidal trend, as represented by fitted curves with R^2 of 0.91 and 0.94 respectively.

5.3.3 SVI and T_r diurnal variation

The calculated SVI, recorded data points for the diurnal T_r , and fitted trends for the full-scale plant, are shown in Figure 5-5. The x_1 -axis indicates the 24-hour diurnal period, the primary y_1 -axis indicates T_r , and the secondary y_2 -axis indicates the calculated SVI reading. Two 2-day profiles, with SVI and T_r correlations R^2 of 0.91, is provided in Figure 10-54 in Appendix F for reference purposes.

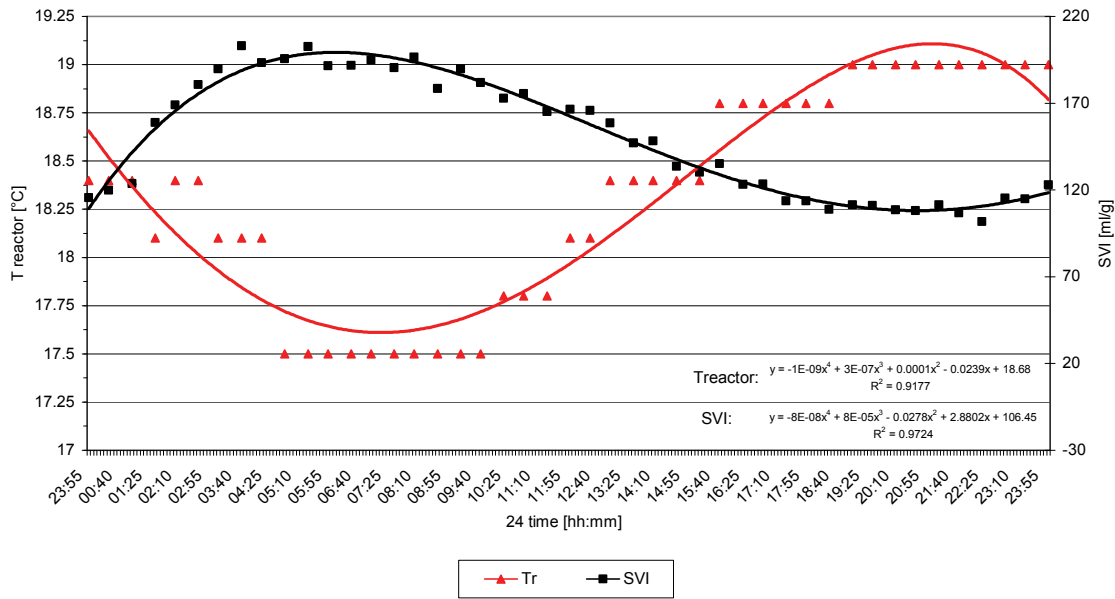


Figure 5-5 Data and fitted curves of temporal variations in T_r and SVI

The full-scale plant average SVI varies by about 100 ml/g per day. This variation was caused by the diurnal MLSS concentration and T_r fluctuations. The SVI profile was relatively smooth over a daily 24-hour period, as shown in Figure 5-5. The T_r and SVI profiles follow sinusoidal trends, as represented by fitted curves with R^2 of 0.92 and 0.97 respectively.

Two 2-day profiles, with SVI and MLSS concentration correlations R^2 of 0.91 and 0.90 respectively, are provided in Figure 10-55 in Appendix F for reference purposes.

5.3.4 Model fitting: SVI dependence on MLSS concentration and T_r

The SVI dependence on MLSS concentration and T_r is statistically evaluated with individual and combined correlations in 2-D and 3-D models.

5.3.4.1 SVI link to MLSS concentration

The recorded data points and a fitted trend for the on-line MLSS concentration and calculated SVI are shown in Figure 5-6. The x-axis indicates MLSS concentration, and the y-axis indicates SVI. The best-fit curve for SVI related to MLSS concentration from full-scale data is represented by a polynomial with a R^2 of 0.69, as shown in Figure 5-6.

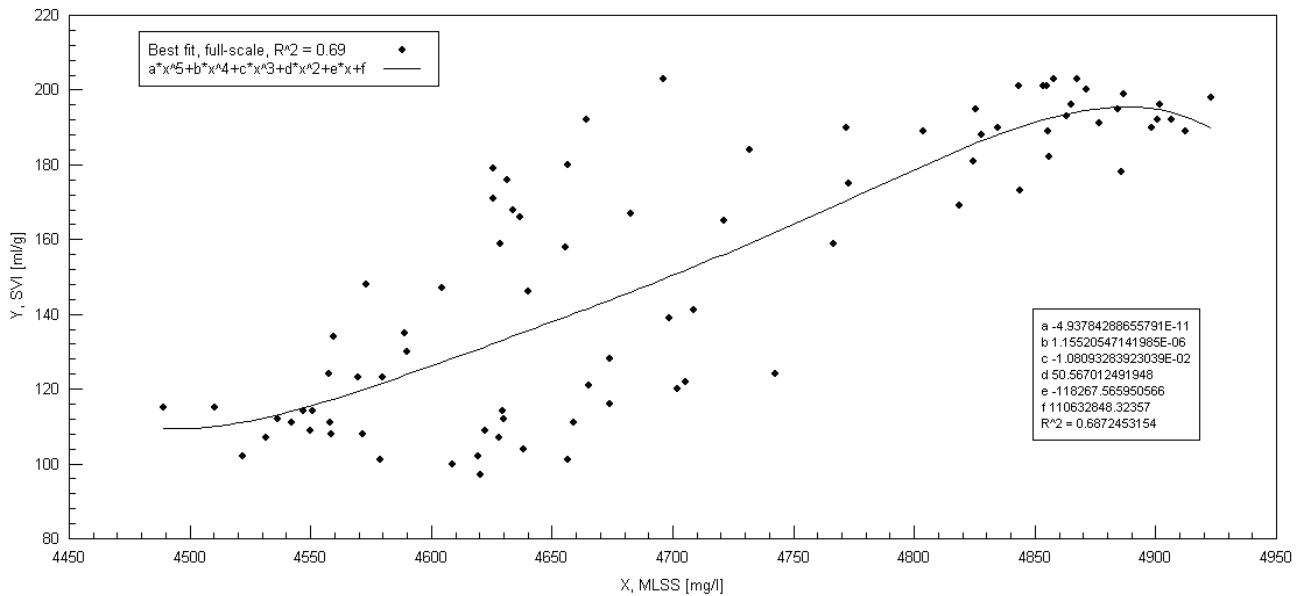


Figure 5-6 SVI related to MLSS concentration

The direct relationship between SVI as the response variable and MLSS concentration as the dependent variable is confirmed by the polynomial, since SVI increases according to the best-fit curve as MLSS concentration increases. The calculated SVI data scatter was visible from 97 to 203 ml/g throughout the MLSS concentration range of 4489 to 4923 mg/l.

5.3.4.2 SVI link to T_r

The recorded data points and a fitted trend for the on-line T_r and calculated SVI are shown in Figure 5-7. The x-axis and the y-axis indicate the T_r and SVI respectively. The best-fit curve for SVI related to T_r for full-scale plant data is represented by a polynomial with a R^2 of 0.38.

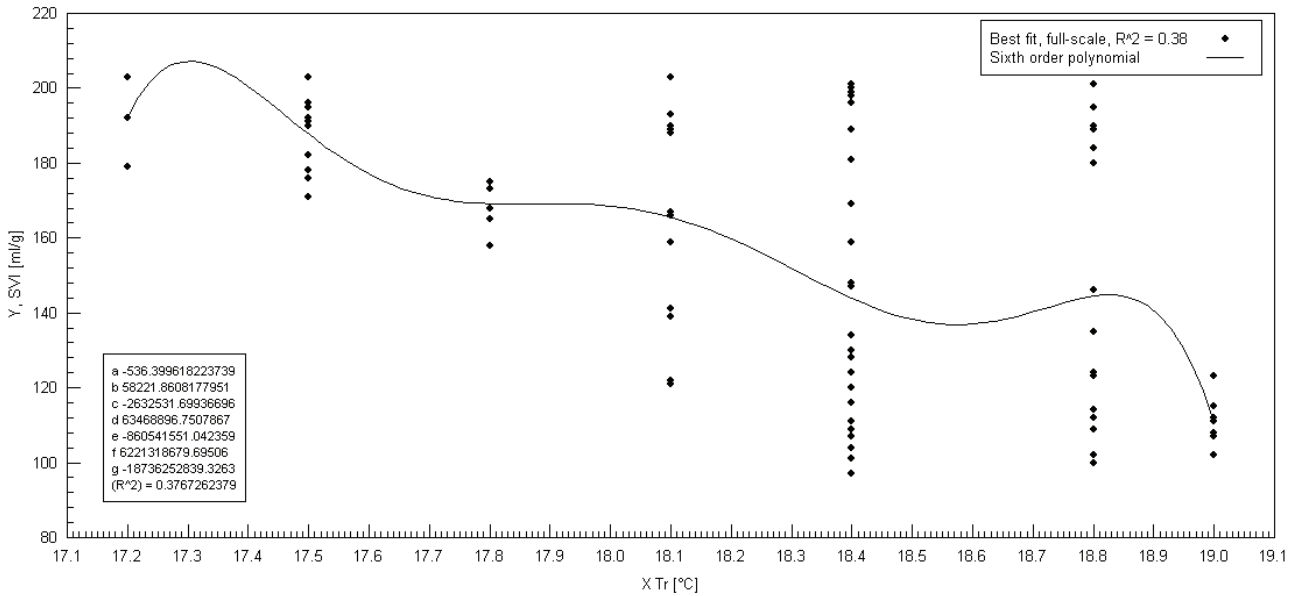


Figure 5-7 SVI data scatter according to T_r variation

The inverse relationship between SVI as the response variable and T_r as the dependent variable is confirmed, since the SVI decreases according to the best-fit curve as the T_r increases. The experimental SVI data scatter was visible throughout the fixed T_r range, since the T_r data logger only recorded in 0.3°C increments.

The large scatter indicates that the SVI data cannot be correlated with only T_r as a single dependent variable. The MLSS concentration is required as a second dependent variable in a 3-D model to reduce the data scatter and to obtain a best-fit correlation for the experimental and calculated data.

5.3.4.3 SVI link to MLSS concentration and T_r

The recorded data points and fitted correlation for the on-line MLSS concentration, the T_r , and the calculated SVI are shown in Figure 5-8. The x_1 -, x_2 - and y-axis represents MLSS concentration, T_r , and SVI respectively. The best-fit curve for SVI related to MLSS concentration and T_r for full-scale plant data was represented on Figure 5-8 by a polynomial with a R^2 of 0.84.

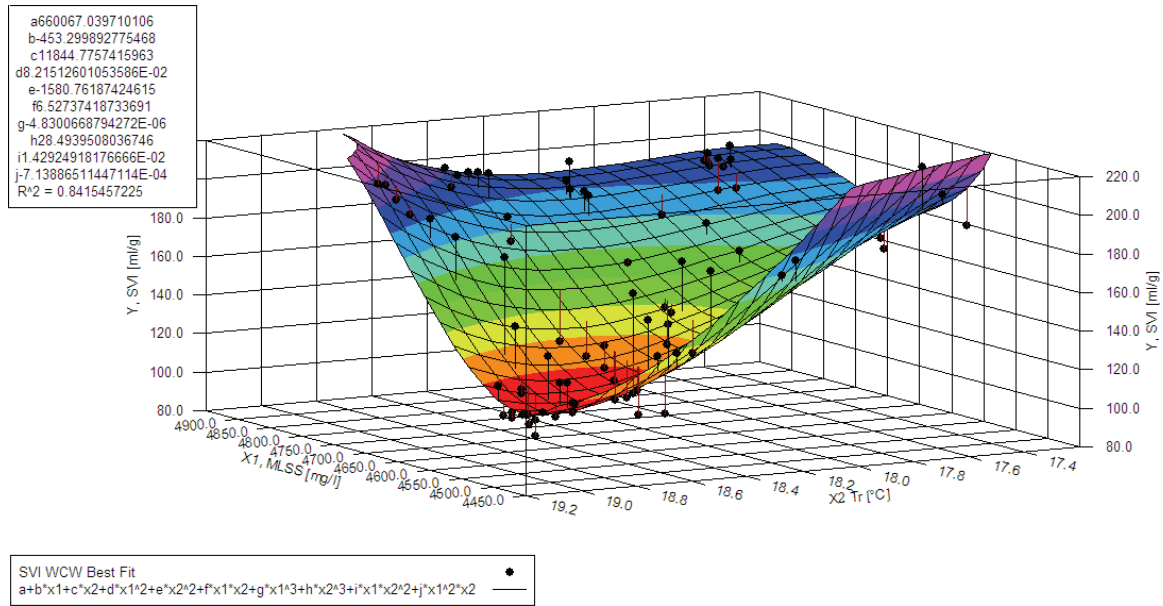


Figure 5-8 SVI related to MLSS concentration and T_r

The temperature impact on settling is demonstrated by the improved curve fitting when T_r data is included in the full-scale plant SVI evaluation. Figure 5-8 illustrates the relationship between SVI as the response variable, with MLSS concentration and T_r as the dependent variables. The SVI response, after a variation in either or both the MLSS concentration and T_r , can be predicted from Figure 5-8.

SVI increases from 97 towards 203 ml/g as the MLSS concentration increases from 4489 to 4923 mg/l and the T_r decreases from 19.0 to 17.2°C. The ideal settling condition, represented by the lowest SVI of 97 ml/g, is obtained at the lowest MLSS concentration and the highest T_r . The inclusion of T_r in the conventional SVI and MLSS concentration correlation improves the curve fitting by a R^2 value of 0.15, from 0.69 to 0.84.

5.3.5 Model fitting: $u_{\max}$ dependence on MLSS concentration and T_r

The $u_{\max}$ dependence on MLSS concentration and T_r is statistically evaluated with individual and combined correlations in 2-D and 3-D models.

5.3.5.1 $u_{\max}$ link to MLSS concentration

The recorded data points and a fitted trend for the full-scale on-line MLSS concentration and calculated $u_{\max}$ are shown in Figure 5-9. The x_1 -axis indicates MLSS concentration and the y-axis indicates $u_{\max}$. The best-fit curve for $u_{\max}$ related to MLSS concentration from full-scale data is represented by a polynomial with a R^2 of 0.58, as shown in Figure 5-9.

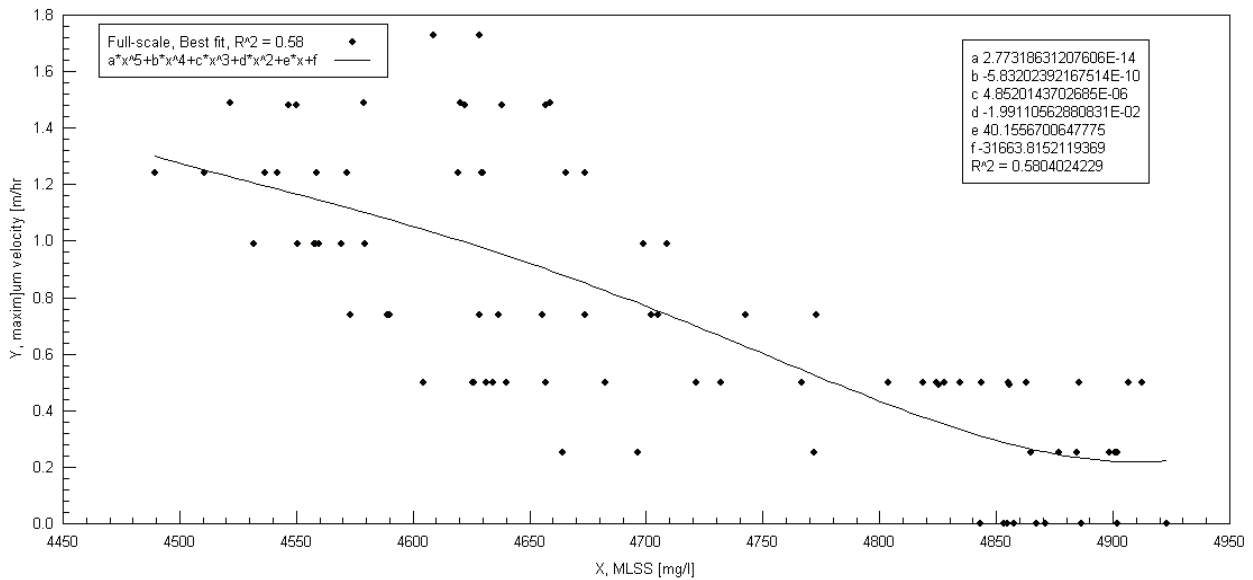


Figure 5-9 $u_{\max}$ related to MLSS concentration

The inverse relationship between $u_{\max}$ as the response variable and MLSS concentration as the dependent variable is confirmed, since the $u_{\max}$ decreases according to the best-fit curve as the MLSS concentration increases. The experimental $u_{\max}$ data scatter is visible from 0 to 1.73 m/hr throughout the MLSS concentration range of 4489 to 4923 mg/l.

5.3.5.2 $u_{\max}$ link to T_r

The recorded data points and a fitted trend for the on-line T_r and calculated $u_{\max}$ are shown in Figure 5-10. The x_1 -axis indicates the T_r and the y-axis indicates the $u_{\max}$. The best-fit curve for $u_{\max}$ related to T_r from the full-scale plant data is represented by a polynomial with a R^2 of 0.26.

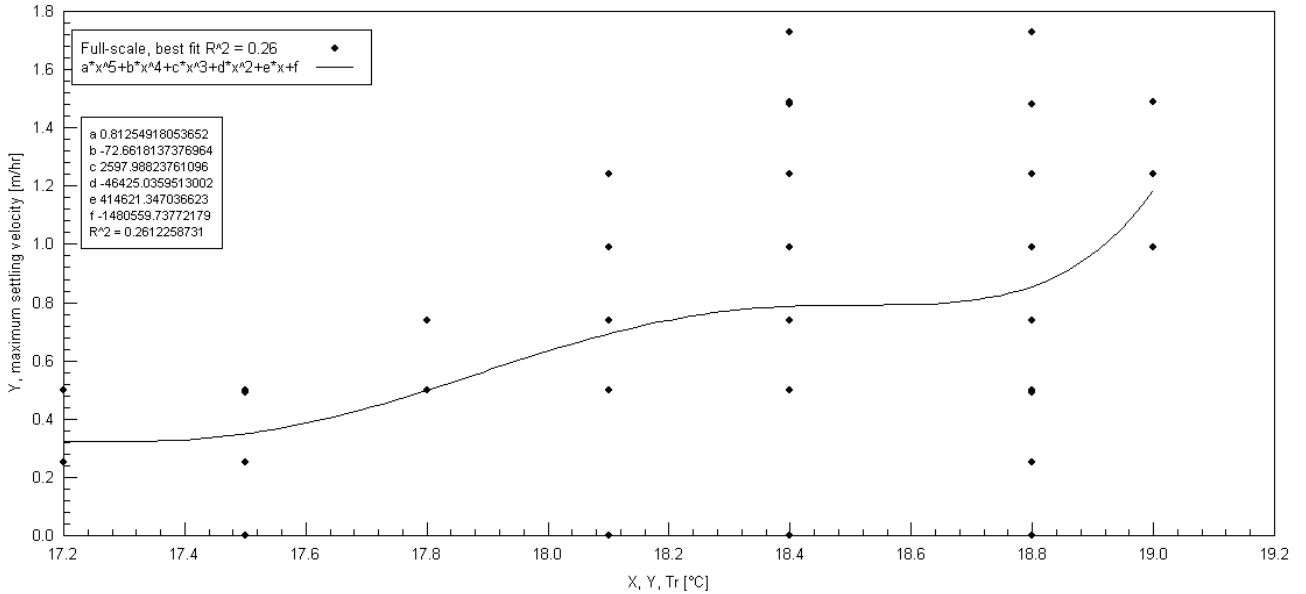


Figure 5-10 $u_{\max}$ data scatter according to T_r variation

There is a poor correlation between $u_{\max}$ as the response variable and T_r as the dependent variable, since the $u_{\max}$ increases according to the best-fit curve as the T_r increases. The large field of experimental $u_{\max}$ data scatter was visible throughout the T_r range increments, since the T_r data logger only recorded in 0.3°C increments.

The scatter indicates that the $u_{\max}$ data cannot be correlated with only T_r as a single dependent variable. The MLSS concentration is required as a second dependent variable in a 3-D model to reduce the data scatter and to obtain a best-fit correlation for the experimental and calculated data.

5.3.5.3 $u_{\max}$ link to MLSS concentration and T_r

The recorded data points and fitted correlation for the on-line MLSS concentration, T_r , and calculated SVI are shown in Figure 5-11. The x_1 -, x_2 - and y -axis represent MLSS concentration, T_r , and $u_{\max}$ respectively. The best-fit curve for $u_{\max}$ related to MLSS concentration and T_r for full-scale plant data was represented on Figure 5-11 by a polynomial with a R^2 of 0.70.

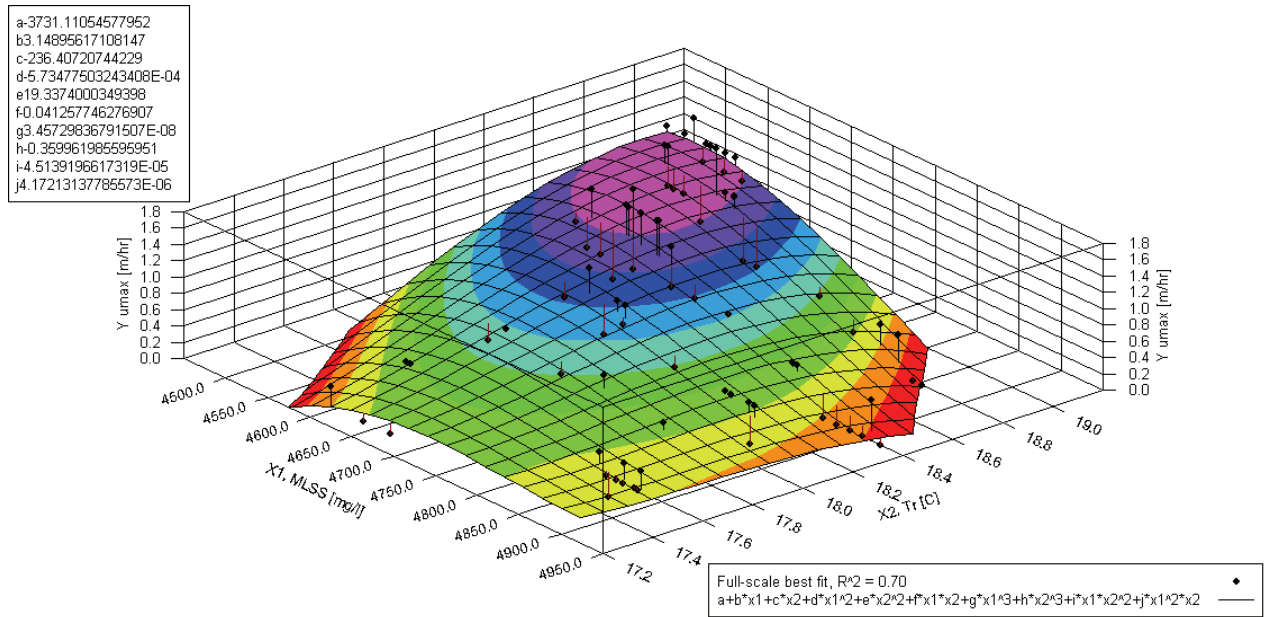


Figure 5-11 $u_{\max}$ related to MLSS concentration and T_r

The temperature impact on settling is demonstrated by the improved curve fitting when T_r data is included in the full-scale plant $u_{\max}$ evaluation. Figure 5-11 illustrates the relationship between $u_{\max}$ as the response variable, and MLSS concentration and T_r as the dependent variables. The $u_{\max}$ response, after a variation in either or both the MLSS concentration and T_r , can be predicted from Figure 5-11.

The $u_{\max}$ increases from 0 towards 1.7 m/hr, as the MLSS concentration decreases from 4923 to 4489 mg/l, and the T_r increases from 17.2 to 19.0°C. The ideal settling condition, represented by the highest $u_{\max}$ of 1.7 m/hr, is obtained at the lowest MLSS concentration and the highest T_r . The inclusion of T_r in the MLSS concentration and $u_{\max}$ correlation improved the curve fitting by a R^2 value of 0.12, from 0.58 to 0.70.

5.3.6 Model fitting: t_{umax} dependence on MLSS concentration and T_r

The t_{umax} dependence on MLSS concentration and T_r is statistically evaluated with individual and combined correlations in 2-D and 3-D models.

5.3.6.1 t_{umax} link to MLSS concentration

The recorded data points and a fitted trend for the full-scale on-line MLSS concentration and calculated t_{umax} are shown in Figure 5-12. The x_1 -axis indicates MLSS concentration and the y-axis indicates t_{umax} . The best-fit curve for t_{umax} related to MLSS concentration from full-scale data is represented by a polynomial with a R^2 of 0.70, as shown in Figure 5-12.

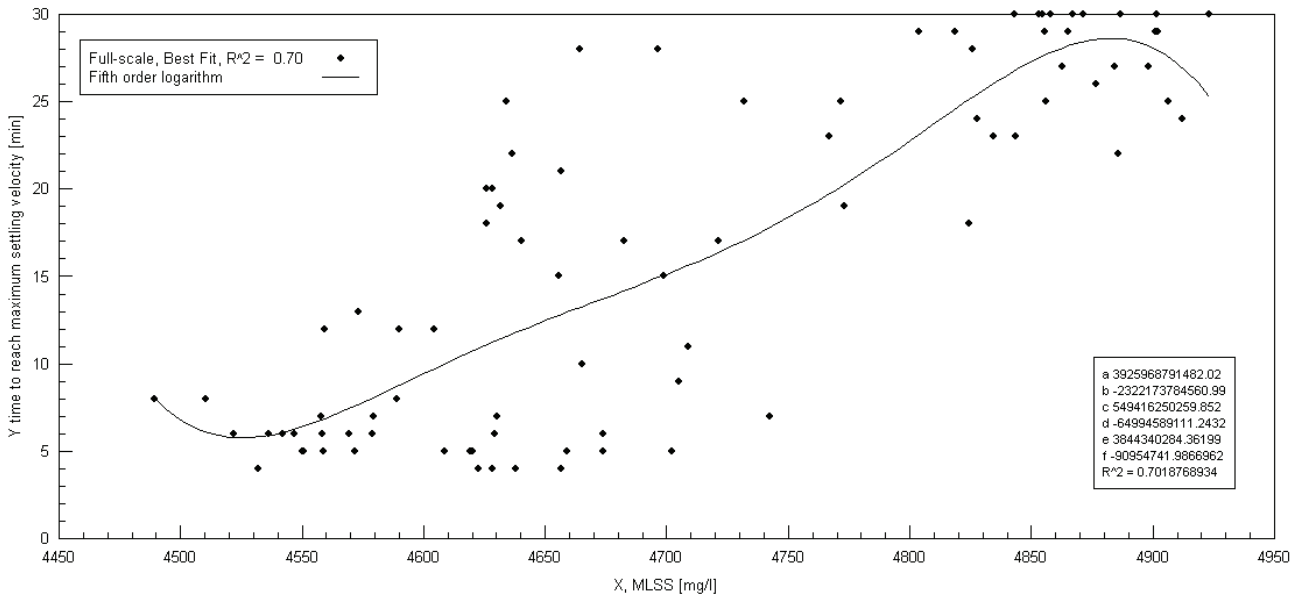


Figure 5-12 t_{umax} related to MLSS concentration

The direct relationships between t_{umax} as the response variable and MLSS concentration as the dependent variable are confirmed, since the t_{umax} increases according to the best-fit curve as the MLSS concentration increases. The experimental t_{umax} data scatter is visible from 4 to 30 minutes throughout the MLSS concentration range of 4489 to 4923 mg/l.

5.3.6.2 t_{umax} link to T_r

The recorded data points and a fitted trend for the on-line T_r and calculated t_{umax} are shown in Figure 5-13. The x_1 -axis indicates T_r and the y-axis indicates t_{umax} . The best-fit curve for t_{umax} related to T_r from the full-scale plant data is represented by a polynomial with a R^2 of 0.32.

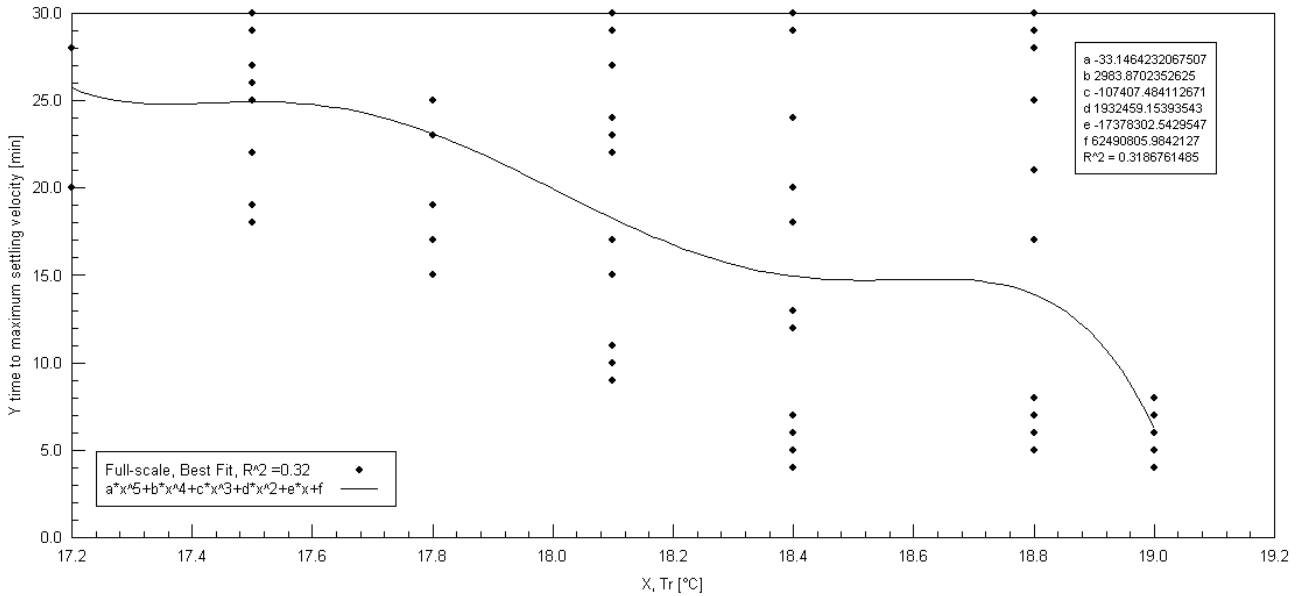


Figure 5-13 t_{umax} data scatter according to T_r variation

There is a poor correlation visible between t_{umax} as the response variable and T_r as the dependent variable, since the t_{umax} decreases according to the best-fit curve as the T_r increases. The large field of experimental t_{umax} data scatter was visible throughout the T_r range increments, since the T_r data logger only recorded in 0.3°C increments.

The scatter indicates that the t_{umax} data cannot be correlated with only T_r as a single dependent variable. The MLSS concentration is required as a second dependent variable in a 3-D model to reduce the data scatter and to obtain a best-fit correlation for the experimental and calculated data.

5.3.6.3 t_{umax} link to MLSS concentration and T_r

The recorded data points and fitted correlation for the on-line MLSS concentration, T_r , and calculated t_{umax} are shown in Figure 5-14. The x_1 -, x_2 - and y -axis represent MLSS concentration, T_r , and t_{umax} respectively. The best-fit curve for t_{umax} related to MLSS concentration and T_r for full-scale plant data was represented on Figure 5-14 by a polynomial with a R^2 of 0.83.

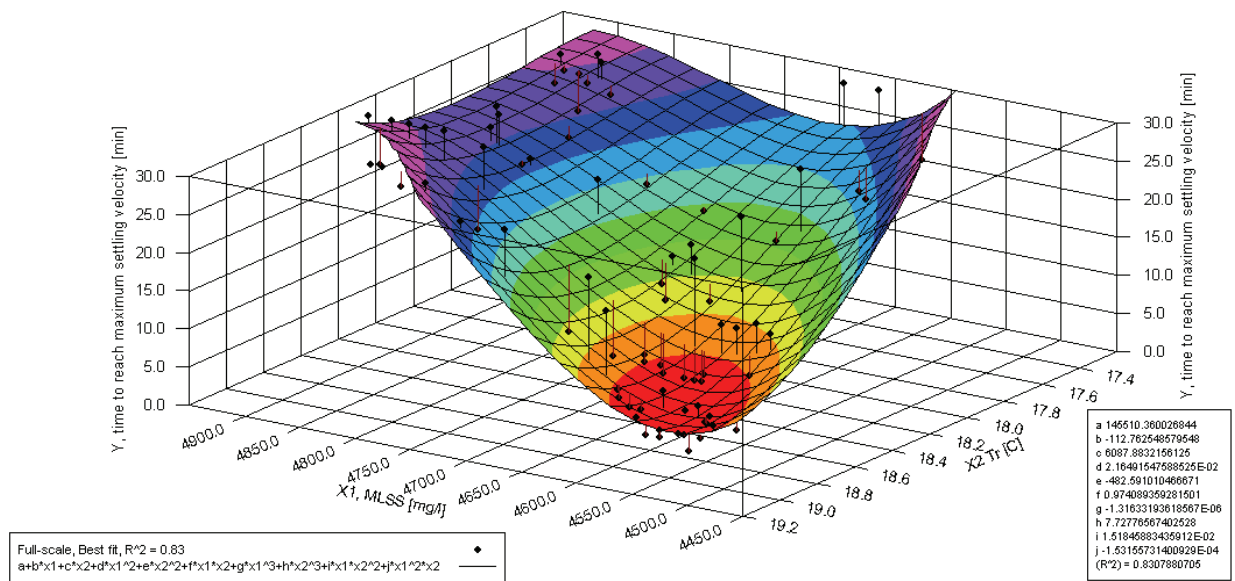


Figure 5-14 t_{umax} related to MLSS concentration and T_r

The temperature impact on settling is demonstrated by the improved curve fitting when T_r data is included in the full-scale plant t_{umax} evaluation. Figure 5-14 illustrates the relationship between t_{umax} as the response variable, and MLSS concentration and T_r as the dependent variables. The t_{umax} response, after a variation in either or both the MLSS concentration and T_r , can be predicted from Figure 5-14.

The t_{umax} increases from 4 towards 30 minutes, as the MLSS concentration increases from 4489 to 4923 mg/l, and the T_r decreases from 19.0 to 17.2°C. The ideal settling condition, represented by the lowest t_{umax} of 4 minutes, is obtained at the lowest MLSS concentration and the highest T_r . The inclusion of T_r in the t_{umax} and MLSS concentration correlation improved the curve fitting by a R^2 value of 0.13, from 0.70 to 0.83.

5.3.7 Model fitting: Summary of curve-fitting correlations

The inclusion of T_r improves the MLSS settling correlations, which is measured according to R^2 increases, as listed in Table 5-2. The average R^2 value for the three MLSS settling parameters (SVI, $u_{\max}$, $t_{\max}$) correlations with MLSS concentration was 0.66 without considering T_r . The inclusion of T_r in the MLSS concentration-based settling correlations improved the average R^2 value by 0.13 to a more acceptable 0.79.

Table 5-2 Best-fit MLSS settling correlations R^2 containing MLSS concentration and T_r

Settling parameter	MLSS concentration R^2	T_r R^2	MLSS concentration and T_r R^2
SVI [mℓ/g]	0.69	0.38	0.84
$u_{\max}$ [m/hr]	0.58	0.26	0.70
$t_{\max}$ [min]	0.70	0.32	0.83
Average	0.66	0.32	0.79

5.3.8 SVI and settling parameter correlation procedure

SVI-based settling parameter correlations are developed experimentally with the on-line settling meter. These temperature dependent SVI correlations can then be used to predict $u_{\max}$ and $t_{\max}$ responses over the operational SVI range, as required for design or operational process control purposes.

5.3.8.1 SVI and $u_{\max}$ correlation

The recorded data points and a fitted trend for the full-scale plant calculated SVI and calculated $u_{\max}$ are shown in Figure 5-15. The x_1 -axis indicates SVI and the y-axis indicates $u_{\max}$. The best-fit curve for $u_{\max}$ related to SVI is represented by a polynomial with a R^2 of 0.90.

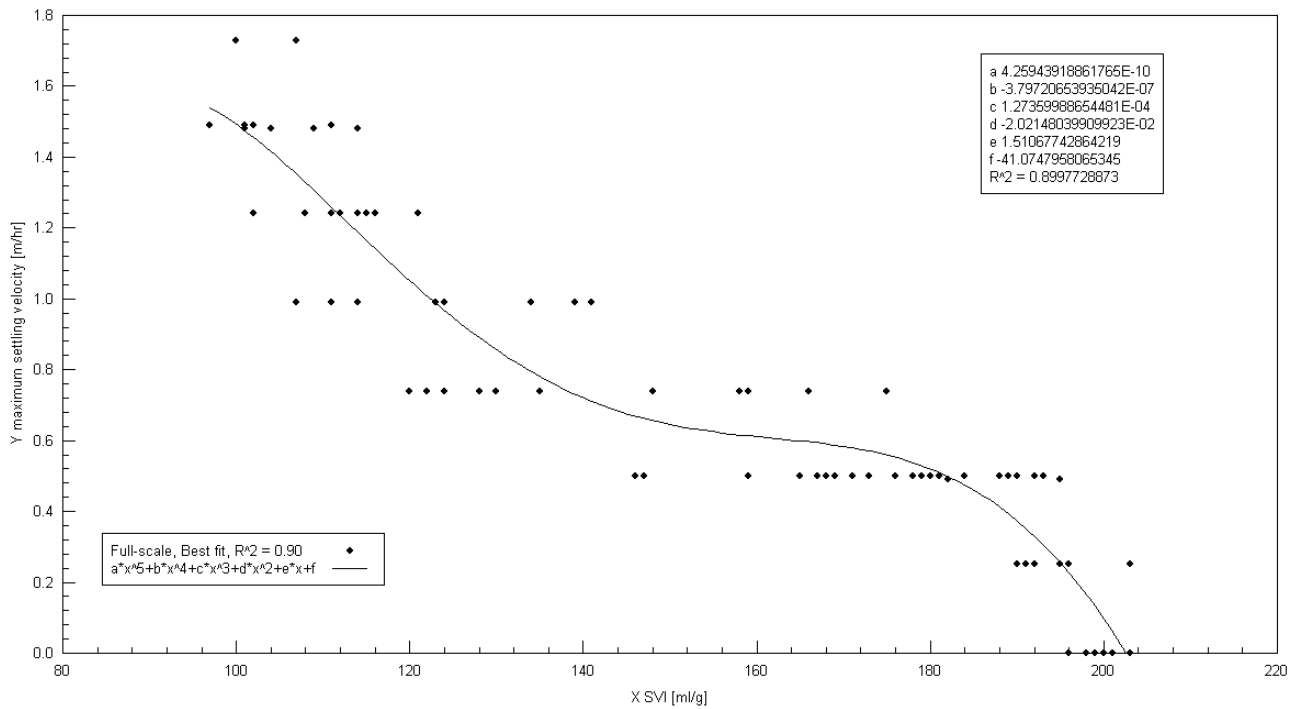


Figure 5-15 $u_{\max}$ related to SVI

The inclusion of T_r in the batch settling tests results in a calculated SVI range from 97 to 203 ml/g that correlates in an inverse relationship with $u_{\max}$ from 1.73 to 0 m/hr. The $u_{\max}$ response can now be predicted for a SVI variation, as shown in Figure 5-15. The good correlation between SVI and $u_{\max}$ confirms the results obtained by Sezgin (1982).

5.3.8.2 SVI and $t_{\max}$ correlation

The recorded data points and a fitted trend for the full-scale plant calculated SVI and calculated $t_{\max}$ are shown in Figure 5-16. The x₁-axis indicates SVI and the y-axis indicates $t_{\max}$. The best-fit curve for $t_{\max}$ related to SVI is represented by a polynomial with a R^2 of 0.95.

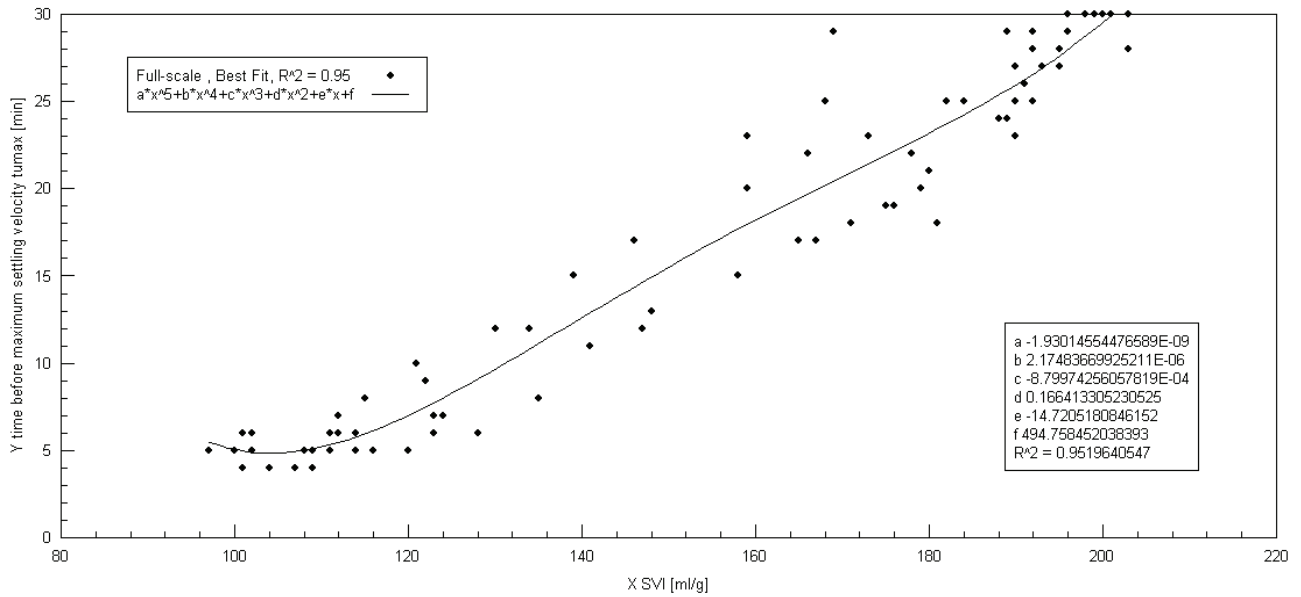


Figure 5-16 t_{umax} related to SVI

The inclusion of T_r in the batch settling tests results in a calculated SVI range from 97 to 203 ml/g that correlates in a direct relationship with t_{umax} from 4 to 30 minutes. The t_{umax} response can now be predicted for a SVI variation, as shown in Figure 5-16. Temperature-based settling correlations containing t_{umax} have not been reported in the available literature.

5.3.9 SVI correlations with u_{max} and t_{umax} : Summary of curve-fitting results

SVI data is obtained from on-line automated settling tests that include T_r variation recordings. The calculated SVI correlation with u_{max} and t_{umax} is summarised in Table 5-3.

Table 5-3 Summary of SVI correlations with u_{max} and t_{umax}

parameter	R^2
u_{max}	0.90
t_{umax}	0.95
average	0.93

The high R^2 values of 0.90 and 0.95 illustrate the effect of T_r during MLSS settling. The temperature-based u_{max} and t_{umax} correlations with SVI, together with the coefficients, are summarised in Table 5-4.

Table 5-4 Coefficients for polynomial: u_{max} and t_{umax} correlations with SVI

coefficient	$y = a * x^5 + b * x^4 + c * x^3 + d * x^2 + e * x + f,$ $x = \text{SVI [ml/g]}$	
	y = u _{max} [m/hr]	y = t _{umax} [minute]
a	4.259E-10	-1.930E-9
b	-3.797E-7	2.175E-6
c	1.274E-4	-8.800E-4
d	-2.021E-2	0.1664
e	1.511	-14.7205
f	-41.075	494.758
R²	0.90	0.95

These on-line-based settling parameter correlations with SVI illustrate the benefits of using automatic settling meters. The settling meters detect the MLSS settling profile at the fluctuating T_r . MLSS settling characteristics are plant specific (Wilén, 2006), and on-line-based correlations will therefore reflect the responses of individual plant settling parameters over operational MLSS concentration and T_r ranges.

An on-line MLSS settling meter can be used to predict the settling characteristics of a BNR plant for design and operational purposes:

- a SVI correlation is developed with on-line reactor MLSS concentration and T_r data (Figure 5-8),
- the complete SVI range can now be predicted from the known or assumed operational MLSS concentration and T_r ranges (Figure 5-8),
- u_{max} and t_{umax} correlations are developed with the predicted SVI range (Figure 5-15 and Figure 5-16), and
- the u_{max} and t_{umax} range could now be predicted from the calculated SVI range (Figure 5-15 and Figure 5-16).

5.3.10 Simplified settling models: MLSS concentration and T_r

The statistical significance of a model, to account for the fraction of the variation among the data points represented by the model, is illustrated by R^2 . Researchers have used R^2 as a general indicator of the statistical significance of settleability models (Daigger, 1995; Ekama *et al.*, 1997), based on batch MLSS settling tests. The following 3-parameter 1st order polynomial function is chosen as the fitted regression model for the 11 settling parameters, based on R^2 and formula simplicity:

$$y = a + \frac{b}{x_1} + \frac{c}{x_2} + \epsilon, (\epsilon \approx (0, \sigma^2))$$

where y is the settling parameter, x_1 is the MLSS concentration [mg/l], x_2 is the T_r [°C], a , b , c are regression constants, ϵ is the random error and σ^2 is the error variance.

This basic model format is easy to use, as summarised in Table 5-5. The 11 equations are a general representation of the experimental data. The data and models is only valid within the experimental MLSS concentration and T_r boundary conditions provided in Table 5-5. Refer also to Table 10-25 in Appendix H for a summary of additional regression variable results. The large t-ratios confirm that all parameters are significant. The low p values indicate that none of the parameters can be removed from the model.

Table 5-5 Summary of regression model constants for settling parameters

Parameter	4489 mg/l < MLSS concentration < 4923 mg/l, n = 85, ave. = 4705, st. dev. 127 17.2°C < T_r < 19.0°C, n = 85, ave. = 18.3, st. dev. = 0.5				
	a	b	c	R ² Simplified	R ² Best-fit
SVI	872.4200	-4624176.0614	4823.4021	0.71	0.84
t _{umax}	239.5623	-1290679.9382	939.9347	0.70	0.83
u _{max}	-9.2997	57454.2585	-39.8603	0.59	0.70
u _{ave}	-2.8943	18433.8191	-15.1792	0.76	0.87
h	1793.9619	-9200670.3014	7744.0213	0.76	0.87
u ₁	-1.1851	14418.7348	-31.9946	0.32	0.45
u ₂	-2.6708	33145.3653	-74.7660	0.59	0.71
u ₃	-3.6732	25152.0675	-26.7192	0.62	0.79
u ₄	-4.1828	19564.9547	3.4218	0.60	0.79
u ₅	-3.3897	11822.7573	18.7500	0.34	0.56
u ₆	-2.6835	8411.5793	18.8984	0.30	0.50

Table 5-6 Regression variable results

Variable	Value	Standard Error 95% (+/-)	Lower Limit	Upper Limit
a	872.4	316.5	555.9	1188.9
b	-46241761	887020.7	-5511196.8	-3737155.4
c	4823.4	3205.9	1617.5	8029.3

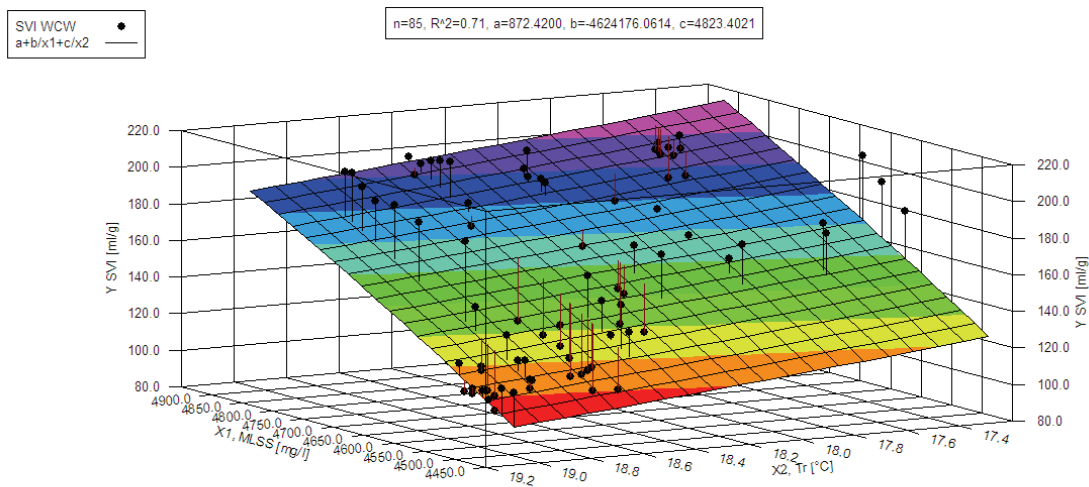
The regression variable results are summarised in Table 5-6 for the standard error confidence interval of 95%. The correlation coefficient of 0.512 between 4624176.1/MLSS and 4823.4/ T_r indicates that the effect of MLSS concentration or T_r on SVI cannot be independently determined.

5.3.10.1 SVI correlation with MLSS concentration and T_r

The response relationship of SVI to MLSS concentration and T_r variations, obtained from the full-scale plant data, is presented by the following regression model, with $R^2 = 0.71$:

$$\text{SVI} = 872.4 - \frac{4624176.1}{\text{MLSS}} + \frac{4823.4}{T_r} \quad [\text{m}\ell/\text{g}] \quad \text{Equation 5-1}$$

The plot of this model is shown in Figure 5-17. The x_1 -axis represents the MLSS concentration range of 4489 to 4923 mg/ ℓ , the x_2 -axis represents the T_r range from 17.2 to 19.0°C, and the y_1 -axis represents the SVI from 96 m ℓ /g to 214 m ℓ /g. The model is represented by a best-fit polynomial with a $R^2 = 0.84$.

Figure 5-17 SVI dependency on MLSS concentration and T_r

The SVI dependence on the full-scale T_r can be illustrated with a simulation. At an average constant MLSS concentration of 4500 mg/ℓ, the SVI change due to a T_r reduction from 19.0 to 17.2°C can be determined according to the SVI-model (Equation 5.1). The SVI increases by 26.5 ml/g, from 98.7 to 125.2 ml/g, with a corresponding relative SVI increase of 14.8 ml/g SVI per 1°C T_r reduction, or -14.8 ml/g SVI/1°C T_r .

This SVI correlation illustrates the extent of batch MLSS settling test result variations. The relatively small temperature reduction of 1.8°C contributes to a SVI increase of 26.5 ml/g. MLSS samples are taken from a reactor at T_r , and they are usually transported, stored, and tested at a different T_s , which could change by much more than 1.8°C.

5.3.10.2 $u_{\max}$ correlation with MLSS concentration and T_r

The response relationship of $u_{\max}$ to MLSS concentration and T_r variations is presented by the following regression model, with $R^2 = 0.59$:

$$u_{\max} = -2.2 + \frac{14785.4}{\text{MLSS}} - \frac{8.3}{T_r} \quad [\text{m/hr}] \quad \text{Equation 5-2}$$

The plot of this model is shown in Figure 5-18. The x_1 -axis represents the MLSS concentration range of 4489 to 4923 mg/ℓ, the x_2 -axis represents the T_r range from 17.2 to 19.0°C, and the y-axis represents the $u_{\max}$ from 0.1 to 1.4 m/hr. The model is represented by a best-fit polynomial with $R^2 = 0.70$.

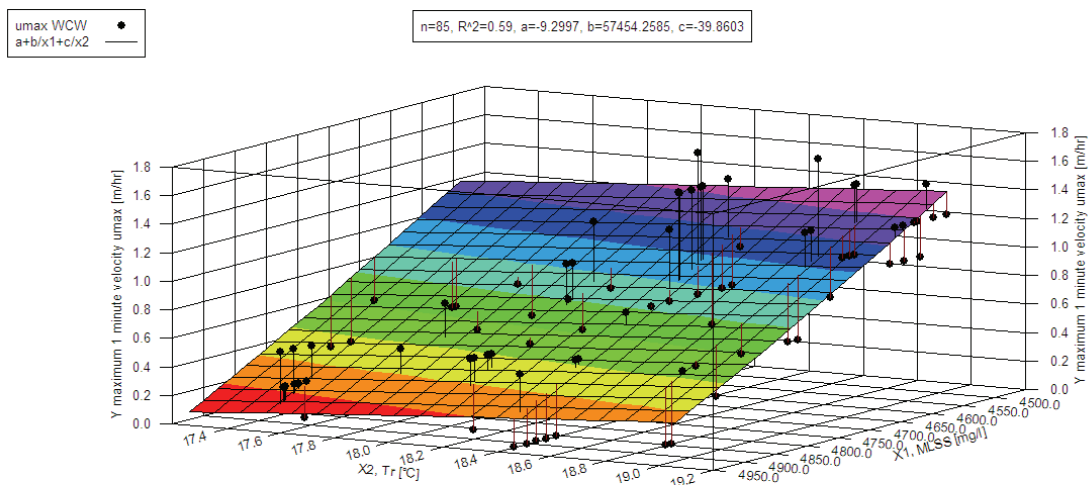


Figure 5-18 $u_{\max}$ dependency on MLSS concentration and T_r

A simulation can illustrate the dependence of $u_{\max}$ on the operational T_r . At an average constant MLSS concentration of 4500 mg/l, the $u_{\max}$ change due to a T_r reduction from 19.0 to 17.2°C can be determined according to the $u_{\max}$ -model (Equation 5.2). The $u_{\max}$ decreases by 0.2 m/hr, from 1.4 to 1.2 m/hr, with a corresponding relative $u_{\max}$ decrease of 0.1 m/hr per 1°C T_r reduction, or 0.1m/hr $u_{\max}$ /1°C T_r .

These correlations have implications for full-scale MLSS settling control. The typical diurnal T_r variation of 1.8°C at a constant MLSS concentration, contributes to an $u_{\max}$ change of more than 0.1 m/hr. From the relatively low T_r dependence of $u_{\max}$, it might be argued that the 1-minute interval in the MLSS settling meter is not sensitive enough to reflect the true zone settling velocity. An improved $u_{\max}$ recording process is required for the on-line settling meter. It is recommended that the MLSS settling meter recording time interval be changed in future applications from 1 to at least 0.5 minutes.

These $u_{\max}$ settling velocity correlations have implications for clarifier design. Secondary tank clarifier design is usually conservative and based on poor MLSS settling characteristics (Van Haandel, 1992). The lower $u_{\max}$ will require a larger secondary settling tank capacity to ensure the solids load can be accommodated at the higher MLSS concentration and the lower T_r .

5.3.10.3 $t_{\max}$ correlation with MLSS concentration and T_r

The response relationship of $t_{\max}$ to MLSS concentration and T_r variations is presented by the following regression model, with $R^2 = 0.70$:

$$t_{\max} = 239.6 - \frac{1290679.9}{\text{MLSS}} + \frac{939.9}{T_r} \quad [\text{minute}] \quad \text{Equation 5-3}$$

The plot of this model is shown in Figure 5-19. The x_1 -axis represents the MLSS concentration range of 4489 to 4923 mg/l, the x_2 -axis represents the T_r range from 17.2 to 19.0°C, and the y-axis represents the $t_{\max}$ from 2 to 30 minutes. This model is represented by a best-fit polynomial with a $R^2 = 0.83$.

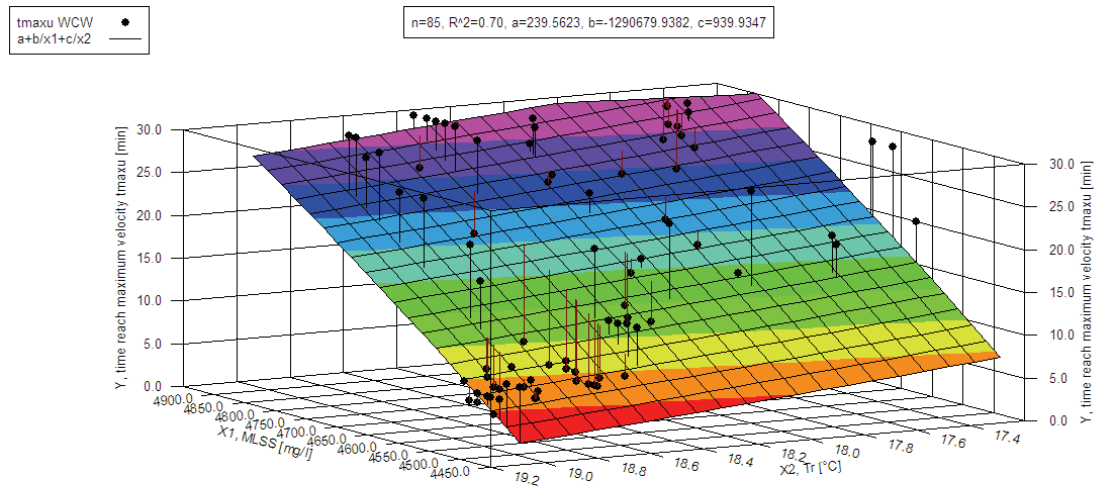


Figure 5-19 t_{max} dependency on MLSS concentration and T_r

A simulation can illustrate the dependence of the t_{max} on the T_r . At an average constant MLSS concentration of 4500 mg/l, the t_{max} change due to a T_r reduction from 19.0 to 17.2°C can be determined according to the t_{max} -model (Equation 5.3). The t_{max} increases by 4.2 minutes, from 2.2 to 6.5 minutes, with a corresponding relative t_{max} increase of 2.4 minutes per 1°C T_r reduction, or 2.4 minute $t_{max}/1^\circ\text{C } T_r$.

These correlations have implications for MLSS settling control and design. The typical diurnal reactor temperature variation of 1.8°C, at a constant MLSS concentration, contributes to a reflocculation time increasing from 2.2 to 6.5 minutes (when u_{max} starts). The reflocculation time delay will require a larger stilling chamber to ensure reflocculation will take place at higher MLSS concentrations and T_r .

The correlations have implications for MLSS sample handling. The dilution of the MLSS concentration of a sample for a DSVI calculation reduces the t_{max} , as the bioflocs can start settling immediately as discrete particles. MLSS sample handling, transport, storage, and tests at a different T_a from T_r can lead to large T_s variations, as well as a corresponding change in minimum reflocculation time (t_{max}).

5.3.10.4 u_{ave} correlation with MLSS concentration and T_r variation

The response relationship of u_{ave} to MLSS concentration and T_r variations is presented by the following regression model, with $R^2=0.76$:

$$u_{ave} = -2.9 + \frac{18433.8}{MLSS} - \frac{15.2}{T_r} \text{ [m/hr]} \quad \text{Equation 5-4}$$

The plot of this model is presented in Figure 5-20. The x_1 -axis represents the MLSS concentration range of 4489 to 4923 mg/l, the x_2 -axis represents the T_r range from 17.2 to 19.0°C, and the y-axis represents u_{ave} from 0 to 0.4 m/hr. This model is represented by a best-fit polynomial with a $R^2 = 0.87$.

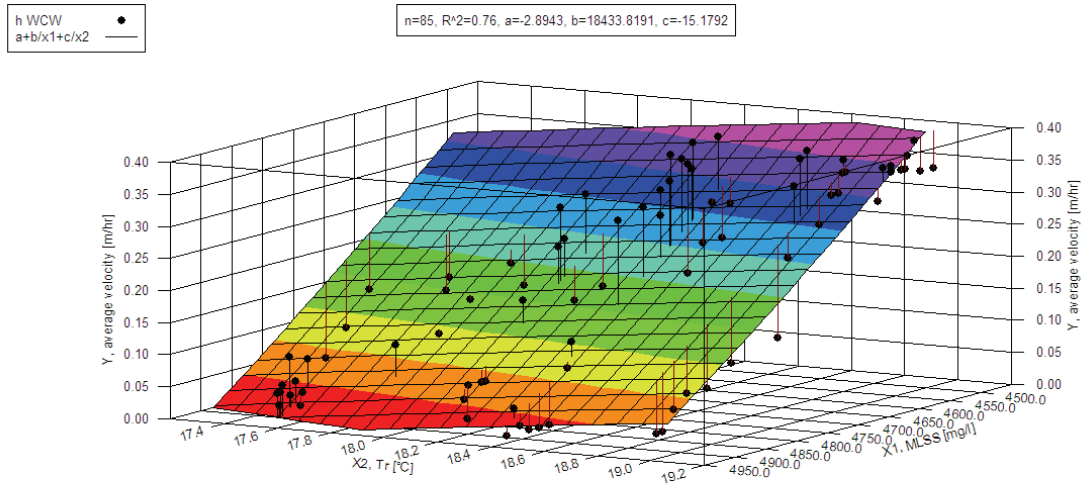


Figure 5-20 u_{ave} dependency on MLSS concentration and T_r

A simulation can illustrate the dependence of u_{ave} on the T_r . At an average constant MLSS concentration of 4500 mg/l, the u_{ave} change due to a T_r reduction from 19.0 to 17.2°C can be determined according to the u_{ave} -model (Equation 5.4). The u_{ave} decreases by 0.1 m/hr, from 0.4 to 0.3 m/hr, with a corresponding relative u_{ave} decrease of 0.04 m/hr per 1°C T_r reduction, or 0.04 m/hr u_{ave} / 1°C T_r .

The u_{ave} over 30 minutes is a rapid indicator of MLSS settling velocity, with the advantage that it can be directly calculated from the SV_{30} (according to the MLSS height settled over 30 minutes). The u_{ave} , as a general settling index, has similar shortcomings to the SVI, specifically regarding the height of the test cylinder or column used. It also does not give an indication of MLSS settling changes occurring during the settling period. The parameter u_{ave} should be used with caution as a general settling indicator. For this project, the principle aim was to demonstrate the T_r dependence of u_{ave} , as shown in Figure 5-20.

5.3.10.5 h correlation with MLSS concentration and T_r variation

The response relationship of h to MLSS concentration and T_r variations obtained from the full-scale plant data is presented by the following regression model, with $R^2 = 0.76$:

$$h = 1794.0 - \frac{9200670.3}{\text{MLSS}} - \frac{7744.0}{T_r} \text{ [mm]} \quad \text{Equation 5-5}$$

The plot of this model is presented in Figure 5-21. The x_1 -axis represents the MLSS concentration range of 4489 to 4923 mg/l, the x_2 -axis represents the T_r range from 17.2 to 19.0°C, and the y-axis represents h from 152 to 355.9 mm. This model is represented by a best-fit polynomial with a $R^2 = 0.87$.

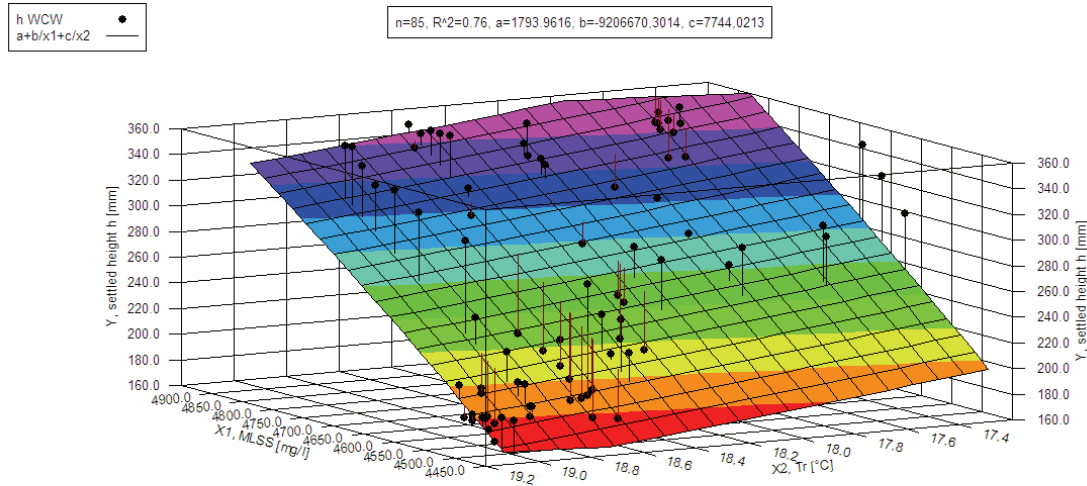


Figure 5-21 h dependency on MLSS concentration and T_r

A simulation can illustrate the dependence of h on T_r . At an average constant MLSS concentration of 4500 mg/l, the h change due to a T_r reduction from 19.0 to 17.2°C can be determined according to the h -model (Equation 5.5). The h increases by 35 mm, from 157 to 192 mm, with a corresponding relative h increase of 19 mm per 1°C T_r reduction, or -19 mm h / 1°C T_r .

5.3.10.6 Incremental velocity u1 to u6 simulation over 30 minutes

The 30-minute settling period is divided in 6 settling periods of 5 minutes each. The average settling velocity over these 5-minute periods is calculated as u1, u2, u3, u4, u5, u6. It was previously demonstrated that MLSS samples will settle faster and sooner (u_max higher and t_umax lower) at lower MLSS concentrations and at higher T_r.

For MLSS samples at a low MLSS concentration and a high T_r, the t_umax will be low and u1, u2, and u3 will therefore be higher. For MLSS samples at a high MLSS concentration and a low T_r, the t_umax will be higher. These MLSS samples will only settle later in the 30-minute cycle, and u4, u5, and u6 will be subsequently higher for these unfavourable MLSS settling conditions (high MLSS concentration and low T_r).

To illustrate the incremental settling velocity changes according to MLSS concentration and T_r, the following 6 sections provide simplified models and regression graphs for u1 to u6.

5.3.10.7 u1 correlation with MLSS concentration and T_r variation

The response relationship of u1 (0 to 5 minutes) to MLSS concentration and T_r variations is presented by the following equation:

$$u1 = -1.2 + \frac{14418.7}{MLSS} - \frac{32.0}{T_r} \quad [\text{m/hr}] \quad \text{Equation 5-6}$$

The model plot is shown in Figure 5-22, and u1 varies on the y-axis from 0 to 0.34 m/hr.

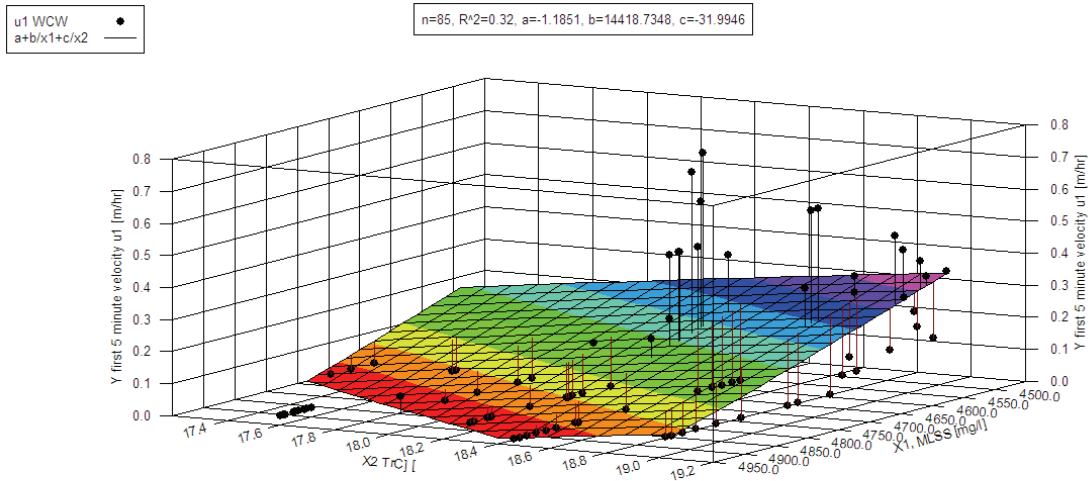


Figure 5-22 u_1 dependency on MLSS concentration and T_r

A simulation can illustrate the dependence of the u_1 on T_r . At an average constant MLSS concentration of 4500 mg/l, the u_1 change due to a T_r reduction from 19.0 to 17.2°C can be determined according to the u_1 -model (Equation 5.6). The u_1 reduces from 0.34 to 0.19 m/hr, with a corresponding relative u_1 decrease of 0.08 m/hr per 1°C T_r reduction, or 0.08 m/hr u_1 /1°C T_r .

The correlation between u_1 and MLSS concentration is not represented in traditional models. The direct correlation between u_1 and T_r is now illustrated with on-line evaluations, at an average of 0.08 m/hr per 1°C change. The correlations can be used as an indication of the reflocculation time. An u_1 settling velocity of 0 m/hr indicates that the MLSS is still in suspension after 5 minutes and that zone settling has not started. The inverse correlation between t_{umax} and T_r is now illustrated for on-line evaluations according to the MLSS settling velocity u_1 .

These correlations can be used together with the reflocculation time to aid in the design of stilling chamber capacity, to ensure bioflocculation will take place at higher MLSS concentrations and lower T_r . The ISV over the first few minutes will determine the loading capacity of the secondary settling tank (Wilén *et al.*, 2006).

5.3.10.8 u2 correlation with MLSS concentration and T_r variation

The response relationship of u_2 (5 to 10 minutes) to MLSS concentration and T_r variations is presented by the following equation:

$$u_2 = -2.7 + \frac{33145}{\text{MLSS}} - \frac{74.8}{T_r} \quad [\text{m/hr}] \quad \text{Equation 5-7}$$

The model plot is shown in Figure 5-23 , and u_2 varies on the y-axis from 0 to 0.78 m/hr.

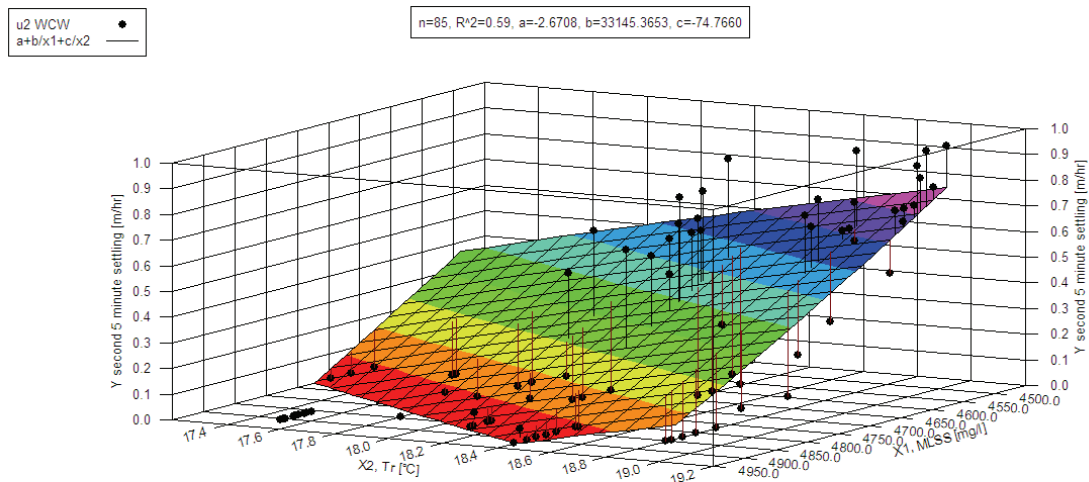


Figure 5-23 u_2 dependency on MLSS concentration and T_r

A simulation can illustrate the dependence of the u_2 on T_r . At an average constant MLSS concentration of 4500 mg/l, the u_2 change due to a T_r reduction from 19.0 to 17.2°C can be determined according to the u_2 -model (Equation 5.7). The u_2 reduces from 0.76 to 0.42 m/hr, with a corresponding relative u_2 decrease of 0.19 m/hr per 1°C T_r reduction, or 0.19 m/hr $u_1/1^\circ\text{C } T_r$.

The correlation between u_2 and MLSS concentration is not represented in traditional models. The direct correlation between u_2 and T_r is illustrated with on-line evaluations, at an average of 0.19 m/hr per 1°C change. The correlation can be used, together with u_1 , as an indication of the reflocculation time. An u_2 settling velocity of 0 m/hr indicates that the MLSS is in suspension after 10 minutes and that zone settling has not started. The

inverse correlation between $t_{u\max}$ and T_r is illustrated with on-line evaluations of the incremental MLSS settling velocity u_2 .

5.3.10.9 u_3 correlation with MLSS concentration and T_r variation

The response relationship of u_3 (10 to 15 minutes) to MLSS concentration and T_r variations is presented by the following equation:

$$u_3 = -3.7 + \frac{25152.1}{\text{MLSS}} - \frac{26.7}{T_r} \quad [\text{m/hr}] \quad \text{Equation 5-8}$$

The model plot is shown in Figure 5-24, and u_3 varies on the y-axis from 0 to 0.52 m/hr.

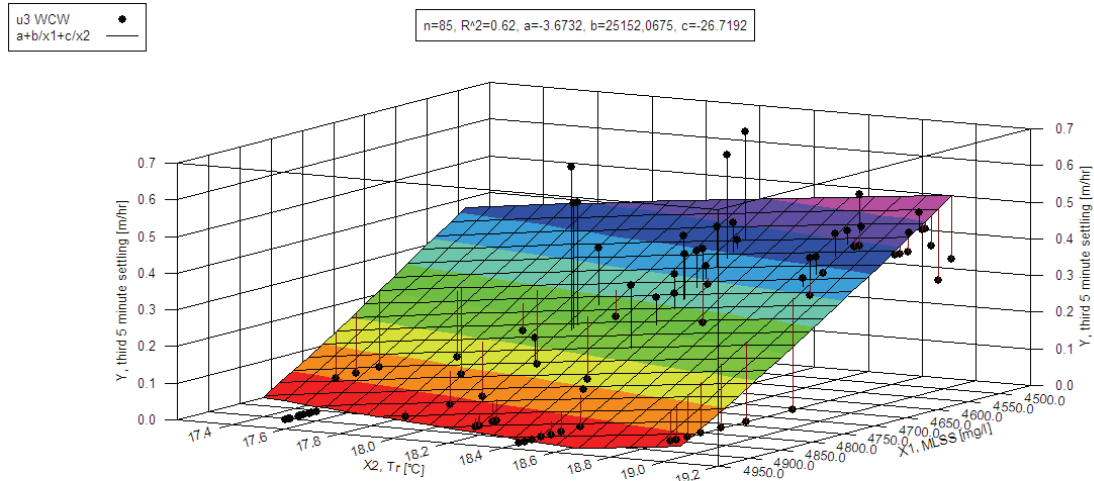


Figure 5-24 u_3 dependency on MLSS concentration and T_r

A simulation can illustrate the dependence of the u_3 on T_r . At an average constant MLSS concentration of 4500 mg/l, the u_3 change due to a T_r reduction from 19.0 to 17.2°C can be determined according to the u_3 -model (Equation 5.8). The u_3 reduces from 0.51 to 0.39 m/hr, with a corresponding relative u_3 decrease of 0.07 m/hr per 1°C T_r reduction, or 0.07 m/hr u_3 /1°C T_r .

The correlation between u_3 and solids concentration is not represented in traditional models. The direct correlation between u_3 and T_r is now illustrated for on-line evaluations, at an average of 0.07 m/hr per 1°C change. The colder MLSS samples at

higher MLSS concentrations only starts to settle after 10 minutes, and the u3 incremental settling velocity is therefore higher at the high MLSS concentration and low T_r ranges.

5.3.10.10 u4 correlation with MLSS concentration and T_r variation

The response relationship of u4 (15 to 20 minutes) to MLSS concentration and T_r variations is presented by the following equation:

$$u4 = -4.2 + \frac{19565.0}{\text{MLSS}} + \frac{3.4}{T_r} \quad [\text{m/hr}] \quad \text{Equation 5-9}$$

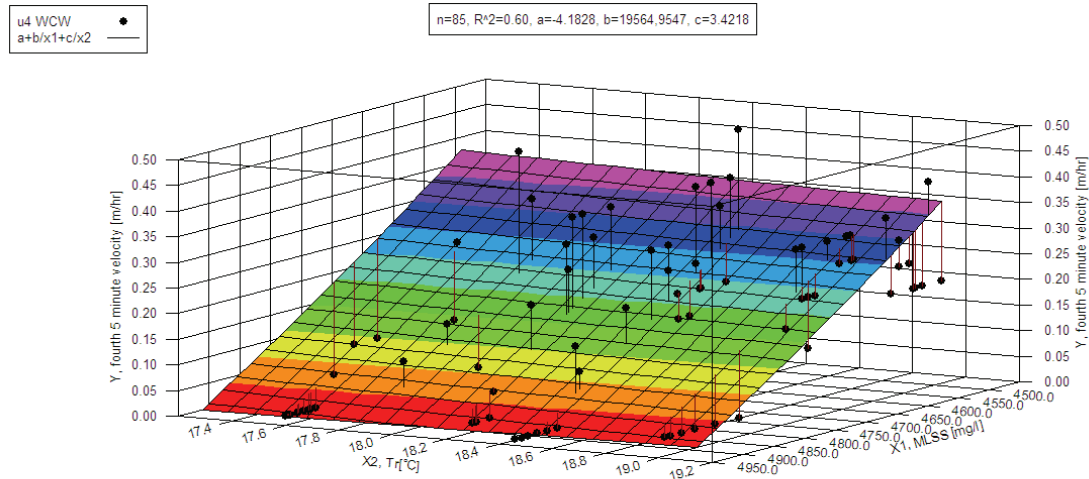


Figure 5-25 u4 dependency on MLSS concentration and T_r

The model plot is shown in Figure 5-25, and u4 varies on the y-axis from 0 to 0.37 m/hr.

A simulation can illustrate the dependence of the u4 on T_r . At an average constant MLSS concentration of 4500 mg/l, the u4 change due to a T_r reduction from 19.0 to 17.2°C can be determined according to the u4-model (Equation 5.9). The u4 increases from 0.35 to 0.36 m/hr, with a corresponding relative u4 increase of 0.01 m/hr per 1°C T_r reduction, or - 0.01 m/hr u4/1°C T_r .

The correlation between u4 and MLSS concentration is not represented in traditional models. The u4 (settling velocity over the fourth 5-minute settling period) follows now a different pattern from previous incremental velocities up to 15 minutes. All the easily

flocculating MLSS at the high temperature has flocculated and settled over these first 15 minutes. The MLSS at the colder temperature only starts to settle after 15 minutes, and u_4 is therefore higher in the low temperature range. The inverse correlation between u_4 and T_r is illustrated from the on-line evaluations at an average of -0.01 m/hr per 1°C change.

5.3.10.11 u_5 correlation with MLSS concentration and T_r variation

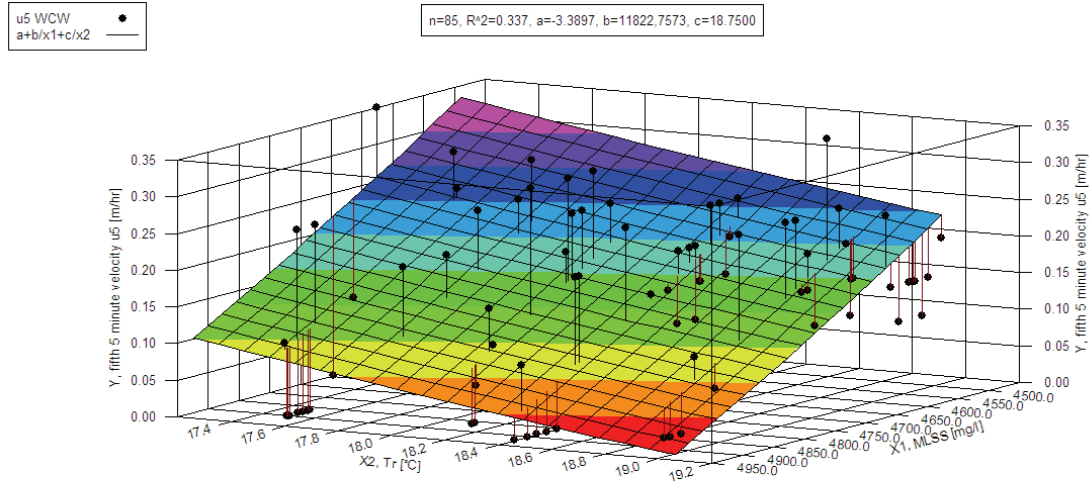


Figure 5-26 u_5 dependency on MLSS concentration and T_r

The response relationship of u_5 (20 to 25 minutes) to MLSS concentration and T_r variations is presented by the following equation:

$$u_5 = -3.4 + \frac{11822.8}{\text{MLSS}} + \frac{18.8}{T_r} \text{ [m/hr]} \quad \text{Equation 5-10}$$

The model plot is shown in Figure 5-26, and u_5 varies on the y-axis from 0 to 0.33 m/hr. A simulation can illustrate the dependence of the u_5 on T_r . At an average constant MLSS concentration of 4500 mg/l, the u_5 change due to a T_r reduction from 19.0 to 17.2°C can be determined according to the u_5 -model (Equation 5.10). The u_5 increases from 0.22 to 0.31 m/hr, with a corresponding relative u_5 increase of 0.05 m/hr per 1°C T_r reduction, or -0.05 m/hr $u_5/1^\circ\text{C } T_r$.

The correlation between u_5 and solids concentration is not represented in traditional models. The settling velocity over the fifth 5-minute settling period now follows the same inverse pattern as identified previously in u_4 . All the easily flocculating MLSS at the high

temperature has flocculated and settled over the first 15 minutes. Some MLSS sample at the colder temperature only start to settle after 15 to 25 minutes, and the settling velocity is therefore higher in the lower temperature range. The inverse correlation between u_5 and T_r is illustrated for on-line evaluations at an average of -0.05 m/hr per 1°C change.

5.3.10.12 u_6 correlation with MLSS concentration and T_r variation

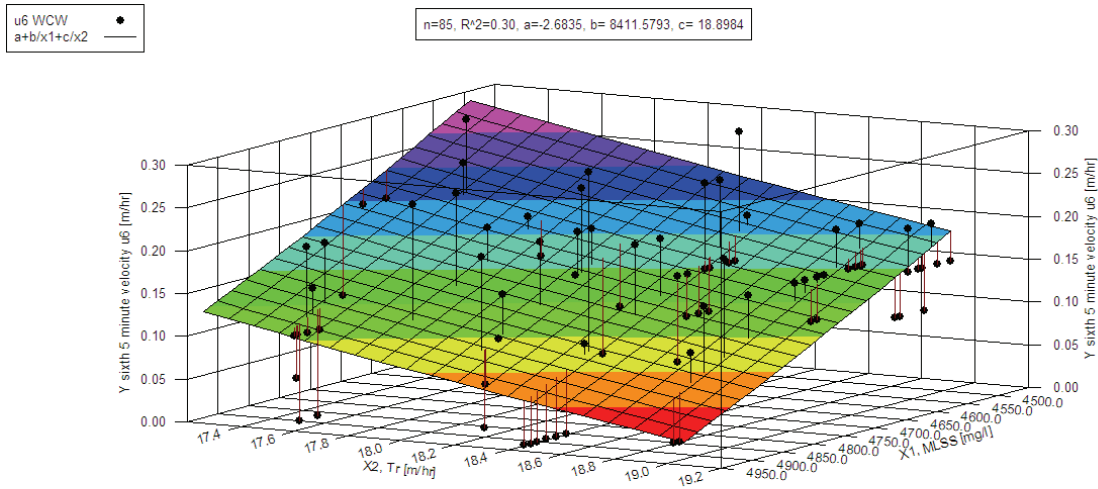


Figure 5-27 u_6 dependency on MLSS concentration and T_r

The response relationship of u_6 (25 to 30 minutes) to MLSS concentration and T_r variations is presented by the following equation:

$$u_6 = -2.7 + \frac{8411.6}{\text{MLSS}} + \frac{18.9}{T_r} \quad [\text{m/hr}] \quad \text{Equation 5-11}$$

The model plot is shown in Figure 5-27, and u_6 varies on the y-axis from 0.02 to 0.29 m/hr.

A simulation can illustrate the dependence of u_6 on T_r . At an average constant MLSS concentration of 4500 mg/l, the u_6 change due to a T_r reduction from 19.0 to 17.2°C can be determined according to the u_6 -model (Equation 5.11). The u_6 increases from 0.18 to 0.27 m/hr, with a corresponding relative u_6 increase of 0.05 m/hr per 1°C T_r reduction, or - 0.05 m/hr u_6 /1°C T_r .

The settling velocity over the sixth 5-minute period now follows the same pattern as identified in u_4 and u_5 . All the easily flocculating MLSS at higher temperatures has

flocculated and settled over the first 15 minutes. The MLSS at the colder temperature only starts to settle after 15 to 30 minutes, and the u_6 settling velocity is therefore higher in the lower T_r range. The inverse correlation between u_6 and T_r is illustrated for the on-line evaluation, at an average of -0.05 m/hr per 1°C change.

5.3.11 Settling models results summary

The experimental range for the settling parameters is provided in Table 5-7. The modelled values differ from the experimental values due to the regression curve-fitting calculations.

Table 5-7 Settling parameters model prediction over experimental range

Parameter	Unit	Minimum experimental parameter value	Minimum modelled parameter value	Maximum experimental parameter value	Maximum modelled parameter value
SVI	[m ³ /g]	97	96.2	203	213.5
t _{umax}	[min.]	4.0	1.5	30.0	32.0
u _{max}	[m/hr]	0.00	0.05	1.73	1.40
u _{ave}	[m/hr]	0.01	-0.03	0.39	0.41
h	[mm]	162.0	151.9	355.9	375.3
u ₁	[m/hr]	0.00	-0.12	0.74	0.34
u ₂	[m/hr]	0.00	-0.28	0.94	0.78
u ₃	[m/hr]	0.00	-0.12	0.69	0.52
u ₄	[m/hr]	0.00	-0.03	0.49	0.37
u ₅	[m/hr]	0.00	0.00	0.35	0.33
u ₆	[m/hr]	0.00	0.02	0.30	0.29

The experimental parameter list is compared to the modelled range for the same parameters, with the minimum and maximum values indicating the comparative predicted values. The model equation can be recalculated with a new parameter range, if the predicted values fall outside the experimental range.

The model equations were not recalculated, as the principle aim of the modelling was to illustrate T_r -based MLSS settling correlations for a full-scale plant-specific experimental condition. The development of more representative parameter models will require additional experimental data over a wider operational range.

5.3.12 Settling models simulation results

An average MLSS concentration of 4500 mg/ℓ is used with the boundary temperature range from 19.0 to 17.2°C to calculate settling parameters. The results are summarised in

Table 5-8. The relative change to settling parameters is based on a 1°C T_r reduction. Direct and inverse relationships are quantified respectively by positive and negative parameter changes.

Table 5-8 Modelled settling parameters simulation based on T_r variation

Parameter	MLSS concentration constant [mg/l]	T_r High [°C]	calculated parameter	T_r Low [°C]	T_r change [°C]	calculated parameter	parameter change	parameter relative change	unit
SVI	4500	19.0	99	17.2	1.8	125	-26.5	-14.8	mL/g/1°C
t_{umax}	4500	19.0	2.2	17.2	1.8	6.5	-4.2	-2.4	min/1°C
u_{max}	4500	19.0	1.4	17.2	1.8	1.2	0.2	0.1	m/hr/1°C
u_{ave}	4500	19.0	0.4	17.2	1.8	0.3	0.1	0.04	m/hr/1°C
h	4500	19.0	157	17.2	1.8	192	-35	-19	mm/1°C
u_1	4500	19.0	0.34	17.2	1.8	0.19	0.14	0.08	m/hr/1°C
u_2	4500	19.0	0.76	17.2	1.8	0.42	0.34	0.19	m/hr/1°C
u_3	4500	19.0	0.51	17.2	1.8	0.39	0.12	0.07	m/hr/1°C
u_4	4500	19.0	0.35	17.2	1.8	0.36	-0.02	-0.01	m/hr/1°C
u_5	4500	19.0	0.22	17.2	1.8	0.31	-0.08	-0.05	m/hr/1°C
u_6	4500	19.0	0.18	17.2	1.8	0.27	-0.09	-0.05	m/hr/1°C

5.4 Summary

A custom-made MLSS settling meter provides semi-continuous MLSS settling profiles for use in settling parameter modelling. The experimental work consisted of four main aspects at a full-scale plant reactor:

1. diurnal variations in h , T_r , MLSS concentration, and SVI,
2. best-fit modelling of three settling parameters (SVI, u_{max} and t_{umax}) with MLSS concentration and T_r ,
3. model fitting of SVI with u_{max} and t_{umax} , and
4. basic modelling and simulation of 11 settling parameters with MLSS concentration and T_r .

The on-line MLSS settling evaluation at a full-scale plant reactor provides the following results:

- The diurnal profiles follow sinusoidal wave profiles, with inverse relationships between T_r and settling meter h , MLSS concentration, and SVI,

- The SVI, $u_{\max}$, and $t_{\max}$ were unsatisfactorily correlated to MLSS concentration alone, with R^2 -values of 0.69, 0.58, and 0.70 respectively. The inclusion of T_r improved the corresponding best-fit correlations to R^2 -values of 0.84, 0.70, and 0.83 respectively, with large t-ratios and low p values indicating the importance of T_r ,
- The temperature-based SVI was correlated to $u_{\max}$ and $t_{\max}$ at R^2 -values of 0.90 and 0.95 respectively,
- The basic 3-parameter settling model provided significant changes for the 11 settling parameter, based on operational T_r variations at constant MLSS concentrations, as summarised in Table 5-8.

5.5 Conclusions

- The governing role of MLSS concentration during MLSS settling might hide the effects of other factors affecting MLSS settling, such as temperature. The settling parameters, such as SVI, mirror the diurnal MLSS concentration profile, but the diurnal temperature fluctuation changes inversely with the corresponding MLSS concentration. The on-line MLSS settling meter collects enough data points based on operational conditions to generate temperature dependent MLSS settling profiles that identify and represent the effects of temperature.
- The small, but significant effect of short-term temperature variation on MLSS settling is proved statistically with improved settling models. Settling parameters are unsatisfactorily correlated with MLSS concentration alone. The inclusion of T_r improved the corresponding best-fit correlations, with R^2 -values increases larger than 0.1 obtained for the full-scale plant data.
- The temperature effect on settling parameters is illustrated with simplified settling models. Simulations illustrate the changes to settling parameter, based on temperature changes at constant MLSS concentrations. The SVI increase of 14.8 mL/g per 1°C T_r reduction is coincidentally identical to batch settling SVI test results (-14.8 mL/g per 1°C T_s). The time to reach $u_{\max}$ increases by 2.4 minutes per 1°C T_r reduction, while the $u_{\max}$ increases by 0.1 m/hr per 1°C T_r increase.

- The incremental 5-minute settling velocity models produce distinctive trends over the 30 minute settling period:
 1. A direct relationship exists over the first 15 minutes between u_1 , u_2 , u_3 , and T_r , similar to the u_{ave} and u_{max} relationships with T_r .
 2. After 15 minutes, the settling trend changes, and for the next 15 minutes u_4 , u_5 , and u_6 change inversely with T_r variations.
 3. MLSS at higher MLSS concentration and lower T_r did not settle over the first 15 minutes, and the colder MLSS only started to settle between 15 and 30 minutes, creating inverse MLSS settling velocity to T_r relationship.
- The modelled settling parameter values are only valid for the experimental boundary conditions, as indicated on the individual graphs. Predictions based on the settling parameter models are invalid outside these MLSS concentration and T_r ranges.
- With the above conclusions, a suitable approach is provided to improve the reliability of MLSS settling tests. The effects of short-term temperature variations before and during MLSS settling tests can be greatly reduced with the use of an on-line MLSS settling meter.

6 SUMMARY OF RESULTS

The results of this project are summarised according to the project aims, with a summary of the experimental results provided in Table 6-1:

- The literature review confirms the lack of temperature compensation procedures and equipment, and the recording of temperature data, required in the determination of MLSS settling parameters. Limited research information is available on operational temperature conditions, and it appears that temperature-based MLSS settleability models are not readily available.
- A preliminary temperature survey at plant reactors identifies short- and long-term T_r fluctuations that follow T_a profiles. Meteorological factors and unidentified plant specific factors influence T_{raw} .
- A batch MLSS settling evaluation indicates that container size and reactor zone sampling points have a limited influence on the SVI and ISV of a well-settling MLSS. Supernatant turbidity improves from the anaerobic zone throughout the reactor up to the end region of the aerobic zone. The immediate environment of the MLSS sample has a direct influence on MLSS settling test results. A 4.3°C temperature increase over 30 minutes, by MLSS sample placement in direct sunshine instead of shade, results in a 63 mL/g SVI decrease. This relationship illustrates the essential need for temperature compensation and environmental conditions recordings during MLSS settling tests
- The diurnal variations in MLSS settling meter data show distinct sinusoidal wave profiles. Best-fit models of settling parameters illustrate with improved statistical data fitting the impact of T_r inclusion in MLSS concentration-based models. The SVI relationships with the two settling parameters u_{max} and t_{umax} reflect the ease of on-line-based parameter correlations development. Simulations of settling parameters with MLSS concentration and T_r illustrate the extent of parameter change during a temperature variation. A 1.8°C diurnal T_r fluctuation results in a 26.5 mL/g SVI change. This SVI increase of 14.8 mL/g per 1°C T_r decrease illustrates the close inverse relationship between MLSS settleability and temperature. Additional parameter relationships that are identified in the project are listed in Table 6-1.

- Incremental settling data indicates that MLSS concentration and T_r determine the t_{umax} , which in turn indicates during which 5-minute period the settling velocity will be the highest. There is a direct relationship between the settling velocity and T_r . The only exception occurs during stages of the incremental settling velocities over 30 minutes. The on-line-based diurnal settling profile indicates that settling velocity increases later in the 30 minute settling period during the high MLSS concentration and low T_r conditions. The colder MLSS sample only starts settling after a longer reflocculation period (e.g. 15 to 30 minutes).
- The significant effects of short-term temperature variations on MLSS settling parameters have been determined experimentally with batch tests and verified on-line at a full-scale plant reactor, thereby achieving the main project aim.

Table 6-1 MLSS settling parameter variation summary

Index or Parameter	Batch MLSS settling tests T, increase Constant MLSS concentration	On-line full-scale plant T, increase Constant MLSS concentration	On-line full-scale plant Constant T, MLSS concentration increase	Relationship with BNR reactor zones
SVI	Inverse, -14.8 m ³ /g/1°C	Inverse, -14.8 m ³ /g/1°C	Direct correlation	Relatively constant
t _{umax}	-	Inverse, -2.4 min./1°C	Direct correlation	-
u _{max}	-	Direct, 0.1 m/hr/1°C	Inverse correlation	-
u _{ave}	-	Direct, 0.04 m/hr/1°C	Inverse correlation	-
ISV	Direct, 0.12 m/hr/1°C	-	-	Relatively constant
h	-	Inverse, -19 mm/1°C	Direct correlation	-
u1	-	Direct 0.08 m/hr/1°C	Inverse correlation	-
u2	-	Direct 0.19 m/hr/1°C	Inverse correlation	-
u3	-	Direct 0.07 m/hr/1°C	Inverse correlation	-
u4	-	Inverse -0.01 m/hr/1°C	Inverse correlation	-
u5	-	Inverse -0.05m/hr/1°C	Inverse correlation	-
u6	-	Inverse -0.05 m/hr/1°C	Inverse correlation	-
Turbidity	Direct 1.42 FNU/1°C	-	-	Reduction through reactor

7 CONCLUSIONS

- The impact of MLSS concentration dominates other MLSS settling factors, according to the format of existing models. The effect of diurnal T_r fluctuations is not easily detected with conventional batch settling tests due to rapid changes in T_s . An on-line MLSS settling meter combines both diurnal MLSS concentrations and T_r fluctuations, to generate temperature dependent MLSS settling models.
- The batch MLSS settling test in a graduated cylinder is the most widely used method to determine settling parameters such as SVI, but temperature compensation is rarely implemented. The significant effect of short-term temperature variations on MLSS sample settling is illustrated with two evaluations (batch and on-line), at an average 14.8 mL/g SVI increase per 1°C decrease.
- There is a direct relationship between MLSS settling velocity and T_r . The only exception occurs during some of the incremental settling velocities. The incremental settling velocities increase in the second half of the 30 minute settling period in the lower T_r range, because the colder MLSS sample only starts settling after a longer reflocculation period. Incremental settling data indicates that MLSS concentration and T_r determine t_{umax} , and it also specifies the highest settling velocity during the six 5-minute settling stages in the 30-minute period.
- Existing MLSS settling parameter models are based on MLSS concentration, without incorporating temperature. The effect that temperature inclusion has on settling models is illustrated with three settling parameter models, where the statistical improvement is shown by an average R^2 increase of 0.13.
- Conventional batch settling equipment and basic procedures are not suitable to effortlessly identify temperature dependent MLSS settling changes over small operational T_r ranges. The settleability impact of diurnal T_r fluctuations and T_s change during sample handling are not easily detected from routine batch MLSS settling tests performed on a daily basis.
- Automated MLSS settling meters are ideally suited to perform semi-continuous settling tests, but these profiles were not linked before to diurnal T_r fluctuations. The effect of diurnal T_r variations on settling parameters is illustrated on a full-scale plant with correlations between SVI and two settling velocity parameters at an average R^2 of 0.93.

- SVI test results are used for operational settleability control and design purposes, but do not include information about MLSS concentration, environmental test conditions or container dimensions. Temperature variations of about 4.3°C during 30-minute settling test periods result in an average SVI change exceeding 60 mL/g. These rapid T_s variations illustrate the need to include reference temperature conditions in MLSS settling reports and experimental methods.
- Temperature is not a process parameter observed at most operational plants. Preliminary temperature recordings indicated significant short- and long-term temperature changes of a few degrees Celsius in plant reactors and at different aeration systems.
- Basic MLSS settling models that are based on fundamental theories are not readily available to simulate dynamic plant temperature conditions. The literature survey indicated a lack of temperature related MLSS settling tests. Temperature compensation procedures or suitable temperature controlled MLSS settling equipment descriptions are for the most part absent.

8 RESEARCH CONTRIBUTION

This project quantifies the significant effects of temperature variations on batch and on-line MLSS settling test parameters. An automated MLSS settling method is introduced to reduce the effects of sample temperature variations observed before and during settling tests. This method is suitable to determine MLSS settling parameters on-line during dynamic operational conditions. The effects of diurnal temperature fluctuations are therefore included in the generation of settling parameters.

A future research need would be to use such an automated MLSS settling meter at a wider selection of plant reactors to develop plant specific settling models. The effects of different reactor temperatures, based on surface or bubble aeration systems, will be represented by distinctive MLSS settling profiles and associated settling parameter correlations. Specific temperature sensitive processes such as nitrification and MLSS settling influences reactor and clarifier design and operation, which will be enhanced with the availability of the improved parameter correlations.

A second research need would be to use an on-line settling meter to measure alternative settling indexes, such as SSVI and DSVI, during diurnal temperature fluctuations. The principle aim of the current project is to illustrate the effects of short-term temperature variations on MLSS settling. Basic settling parameters are modelled to illustrate the temperature effect, without considering the limitations of certain settling parameters and test methods, such as the SVI. Future temperature-based SSVI and DSVI models will be beneficial for the management and design of wastewater treatment plants.

The established BNR reactor design procedures, which are used in countries with extreme weather patterns such as South Africa, consider long-term T_r fluctuations to ensure nutrient removal is guaranteed at a low T_r . In future, this lowest operational T_r should be included in secondary settling tank design. Specific reactor design to limit the effect of meteorological factors, as well as the use of bubble aeration applications, are two design steps that can be promoted to reduce the lowest operational T_r . The future inclusion of modelled and plant specific T_r -based plant performance data, obtained from on-line MLSS settling meters, establishes opportunities to optimise not only BNR, but also improve secondary settling tank design.

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10 APPENDICES

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10.1 Appendix A1: Pilot plant information

10.1.1 Introduction

An overview of the components and operation of the pilot plant will be presented, followed by background information on the pilot plant operation and plant condition. This chapter is arranged under the following sections:

- Pilot plant
- Monitoring and control systems
- MLSS settling meter
- Experimental periods
- Sampling and laboratory analysis

10.1.2 Research strategy

Ad hoc batch settling tests results in Chapter 4 indicates that MLSS settleability is sensitive to temperature variations under operational test conditions. A pilot plant is used to simulate continuous BNR process conditions. An automated MLSS settling meter is used on this pilot plant reactor to trend the settleability changes over diurnal periods. Full-scale MLSS settleability evaluations are based on the pilot plant temperature based settling data. The diurnal MLSS concentration, temperature and settling meter height profiles are the basic settling parameters to be required for ensuing parameter modelling.

10.1.2.1 Research methodology

The extended construction and commissioning of the pilot plant and settling meter caused delays in the completion of experimental work. The final 3-month duration of the pilot plant operation produces sufficient data, with over 300 settling profiles obtained from the settling meter, to ensure representative MLSS settling profiles are available. Full-scale reactor MLSS settleability tests, resulting in more than 80 settling profiles, verified the experimental pilot plant results.

The manual batch MLSS settling tests results relate to the on-line data as similar temperature dependant settling trends are identified. The batch test conditions can create certain MLSS settling parameter changes. Temperature control during these batch MLSS settling tests is, however, the most difficult aspect of the batch settling tests. On-line tests benefits will therefore relate to the inherent temperature compensation of the automated method.

10.1.2.2 Research instruments

The major research instruments are the pilot plant and the settling meter, which were both developed to monitor continuously settleability variations over successive 24-hour periods. The pilot plant allows the opportunity to simulate operational BNR reactor process conditions under extended temperature fluctuations. The settling meter is ideally suited to detect settleability changes through comparisons of succeeding 30-minute settling profiles.

10.1.3 Pilot Plant

A large part of the project is based on experimental results obtained from an automated settleability evaluation of pilot plant MLSS, together with manual batch settling tests and full-scale reactor MLSS settleability monitoring. The following sections provide a brief overview of the pilot plant components. Additional information is provided on specific challenges related to raw sewage use on small-scale installations.

10.1.3.1 Introduction

The pilot plant is designed to simulate conventional BNR processes, to treat a domestic wastewater containing a substantial industrial component. The plant is used to study methods of monitoring and enhancing the settling properties of activated sludge MLSS. The ERWAT Olifantsfontein WCW raw sewage inflow (screened and dewatered) is used as a continuous feed source of about 2.5 m³/d.

The process train of twelve 220 l plastic drums, constructed on a skid platform to facilitate gravity transfer and designed with interchangeable internal recycle supplies to zones to accommodate most standard process systems, was therefore co-designed and manufactured by a private company (Aquaplan) as part of the WRC project scope. Automated on-line DO control and on-line redox and suspended solids monitoring instrumentation was supplied and installed by another private company (Instrulec) as part of the WRC project scope. Additional work included the development of equipment for the settling meter and on-line monitoring equipment, and to implement some pilot plant modifications.

ERWAT and Instrulec were responsible to develop and commission an operational on-line MLSS settling meter, according to the project objectives.

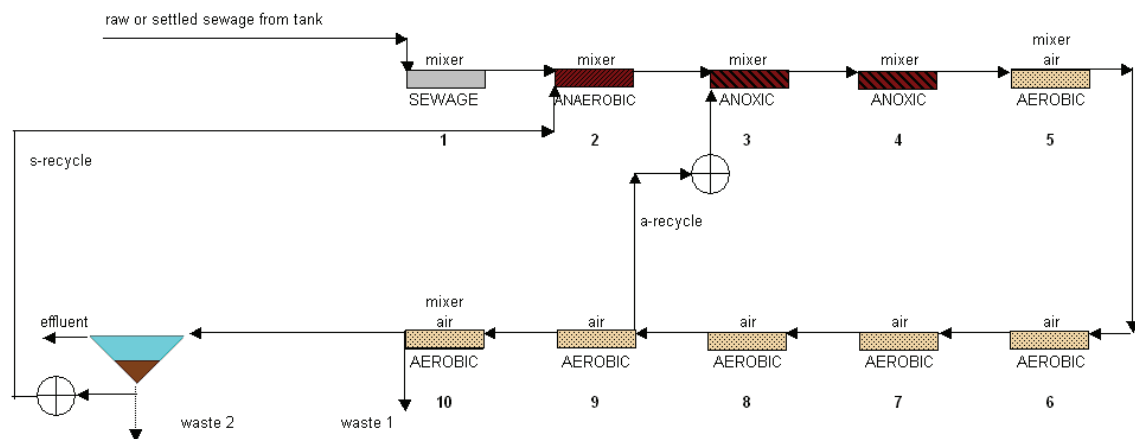
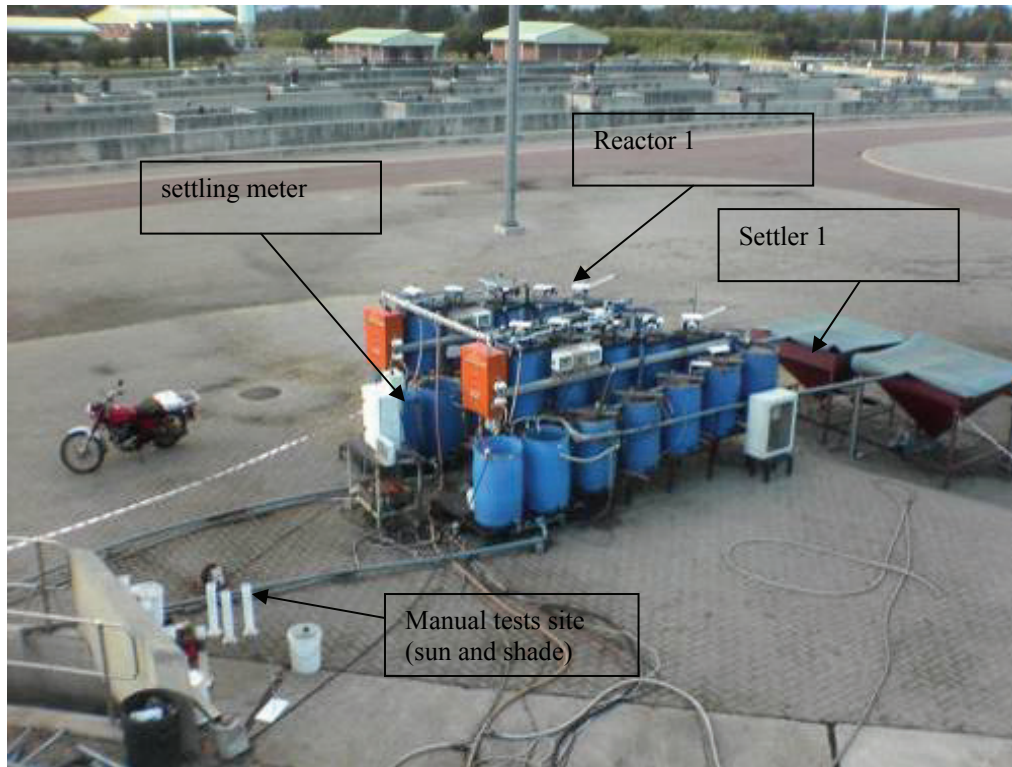


Figure 10-1 Schematic diagram of pilot plant configuration

The pilot plant is required to operate continuously with a raw sewage feed, with minimal supervision during normal working hours, and no supervision after hours. Some of the originally installed components were under specific operational circumstances not suitable for long-term operation, with the presence of inert foreign material and debris in the raw sewage leading to most equipment failures. The following sections give a brief description of the final arrangement and functioning of the pilot plant components.

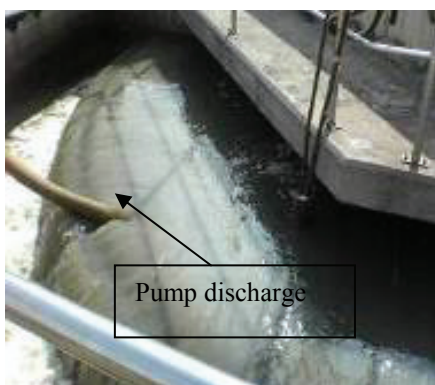


Photograph 1 General pilot plant arrangement

Photograph 1, taken from top of the raw sewage storage tank, indicates the position of the pilot plant next to the WCW flow division unit, as well as the main components of the plant set-up. A schematic diagram of these components is provided in Figure 10-1. The 10 reactor tanks, with various methods of mixing or aeration installed, as well as different process streams controlled by gravity flow or pumps, are indicated in this diagram.

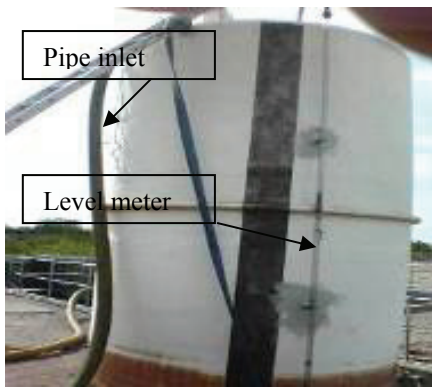
10.1.3.2 Raw sewage supply

- Storage tank feed

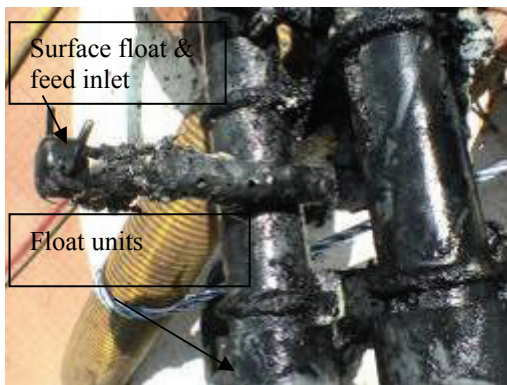


Photograph 2 Feed point for pilot plant from WCW division box

A submersible pump is placed inside the WCW division box, and the pump is connected with a flexible pipe to the top inlet of a 20.4 m³ fibreglass tank, situated next to the inlet flow division box of the WCW. Screened (40 mm and 20 mm) and degritted raw sewage is pumped into the storage tank. Refer to Photograph 2 and Photograph 3.



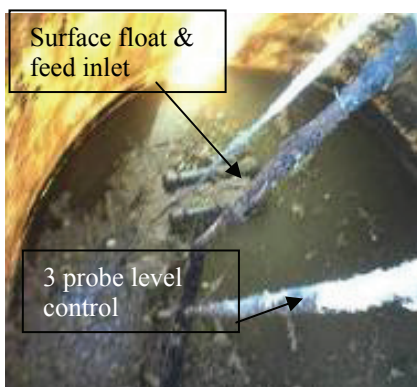
Photograph 3 Storage tank with pipe inlet and tank level indicator



Photograph 4 Float with feed inlet under surface

- Storage tank level control

The storage tank level is controlled by a height adjustable three-probe contact level control system (pump electrical signal connected to earth, live and neutral circuit at different galvanized pipe height levels). To facilitate a feed of 2.5 m³/day to the pilot plant, the level control system, with an approximate 5 cm tank content height variation, controls an available static head of approximately 1 m. A visual tank level indicator (inverted cat and mouse float) displays the tank level on the outside. Refer to photograph 3 and 4.



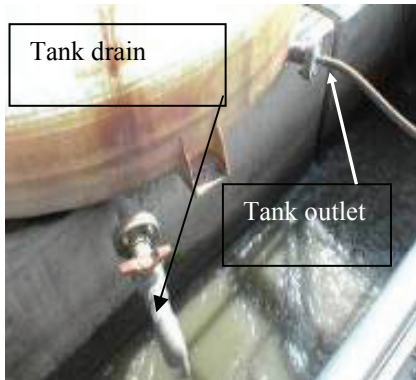
Photograph 5 Tank level control

The tank height is sufficient to ensure the constant flow of sewage under gravity (without valve control and restrictions, which tends to block the pipe flow at low flowrates) from the storage tank to the two pilot plant inlet. Every day the tank drain valve is opened (Photograph 6) to drain heavy sediment from the tank floor and to replace about half the tank content to

ensure the sewage supply stays fresh. The storage tank content is therefore replaced every two days.

- Sewage feed conditioning

A submersible pump can be placed inside the tank to keep the raw sewage permanently in suspension. If a feed of settled sewage is required, the pump can be switched off, to supply settled sewage via the top float delivery, and the settled solids are be drained via a hand valve from the bottom of the tank. The internal tank pump is removed from the tank as the pump suction mesh grid blocked up frequently, due to the large amount of fibrous foreign material in the sewage.



Photograph 6 Tank outlet drain

- Sewage tank outlet

The suction pipe inlet is below the storage tank surface level, attached to a float (made of two 50 mm sealed pipe sections) floating in the tank, to prevent floatable debris on the tank surface from entering and blocking the pipe or downstream systems. The floating decanter is connected to the flexible feed pipe, which is connected to the outlet of the tank. Refer to Photograph 4. This inlet pipe section was finally lowered from 15 to 30 cm below the tank surface as the holes were partially blocked by unseparable floating material, mostly fats and fibres, which were drawn from the tank surface into the feed line.

10.1.3.3 Pilot plant inlet

- Flow control

A small pump was designed to pump sewage from the storage tank to the pilot plant. The constant 2.5 m³/day required is however now controlled directly from the supply tank level. The original feed transfer pump was started once a day for a few minutes to flush the pipelines from sediment that collects in the pipes due to the low linear velocity. This line is now manually flushed with wash water on a daily basis. Refer to Photograph 7.



Photograph 7 Pilot plant supply and tank inlet

The flow inlet pipes have been removed from inside (near the bottom of) the first tank, discharging now onto the surface, to prevent backpressure in the pipes and to ensure a visual indication of true inflow. Refer to Photograph 7. The feed line and supply pipes are flushed daily through drain valves to remove settled deposits from the inlet pipes.

- Tank 1

The sewage enters this tank and mixes the content to ensure a uniform feed. No other recycle streams enter this zone, although it can be used as an anoxic selector, with the introduction of the s-recycle stream.

10.1.3.4 Anaerobic zone

- Tank 2

The s-recycle pipe enters this tank. The inlet pipe has been shortened to end on top of the tank surface, as there was gravity suction flow back out of this tank into the final settling tank. The top outlet ensures a visual indication of true return RAS inflow. A NRV installed on the RAS pump discharge pipe prevented this backflow (and unsettling of sludge in the clarifiers) and the s-recycle pipe outlet was therefore placed inside the tank. Refer to Photograph 8.

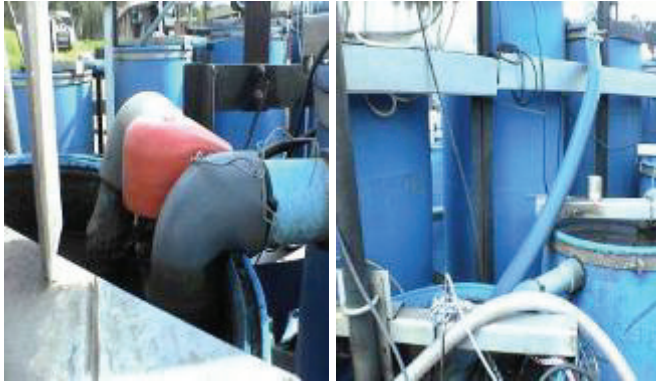


Photograph 8 The s-recycle inlet into tank 2

10.1.3.5 Anoxic zone

- Tank 3

This tank receives the a-recycle flow from the last aerobic tank. A submersible pump is switched to a timer to facilitate a-recycle. Refer to Photograph 9.



Photograph 9 The a-recycle inlet into tank 3 and transfer pipe

- Tank 4

This tank is the second anoxic tank in series, and it does not receive any recirculation flows.

10.1.3.6 Aerobic Zone

- First three tanks (nr 5, 6, 7)

The design was for the air supply to be switched on permanently in the first three tanks. Refer to Photograph 10. A DO meter was then placed into tank 5, and the DO set point for the first 3 aerobic tanks was kept at 2.5 mg/ℓ. Air flow control was done via a standard open-close solenoid valve.



Photograph 10 First three aerobic tanks and air control valve

The air supply to each diffuser has a hand control valve to adjust individual tank DO levels. Normal operational DO control is to keep the DO valves open and control the total supply with main inlet valve, according to the air rota meter (Dwyer, 0-100 ℓpm) reading. The diffuser disc system has been modified with an additional weight (second brick) to enable discs to stay flat at the bottom of tank.

- Last three tanks (8, 9, 10)

A DO concentration meter is used to measure the DO concentration in the last tank, and the airflow is controlled via a solenoid valve in the air supply line.



Photograph 11 DO concentration meter in last aerobic tank and solenoid valve

10.1.3.7 Gravity sedimentation tanks

The designed hydraulic waste system, with sludge pushed out of a pipe fitted to the side of the settling tank, did not function, as sludge accumulated in bottom corners due to the relatively low flows through the tanks and the low hydraulic head. The tanks were then modified with an outlet in the centre of the flat bottom, but sludge still accumulated on the inside slopes. The tanks were then fitted with small concrete funnels at a sloping angle of about 35° to facilitate drainage, but the sludge still accumulated in the corners, due to the rough surface and low slope.

Backflow in the pumping system was then discovered to be the major reason for continued inability of the settling tanks to clarify properly. After the automated RAS sequence stopped, water flowed back into the settling tank, upsetting the blanket and resuspending solids. NRVs were successfully installed at the pump discharge point to prevent this backflow.

Two 0.85 m^3 steel settling tanks, free of charge supplied from another research project, were then refurbished and incorporated into the pilot plant configuration. The pyramid shaped tanks had slopes varying from 45° in the corners to 52° on the sides. This was however not sufficient to ensure gravitational sludge settlement. The tanks were then modified with additional plates to form a new pyramid, to ensure it has slopes varying from 53° in the corners to 60° on the sides. The absence of a large top hydraulic pressure will necessitate the physical scraping of sidewalls, at least on a weekly basis. An old dewatering press belt was placed over the tank surface as a cover, to prevent excessive algae growth induced by sunshine. Refer to Photograph 12.

The RAS pumps were then replaced with old sampler pumps, which showed promise as a reliable sludge transfer system. The installed 12 V power supply had however not a tripping function, and the motors were damaged when the pump rotating mechanism became defective. Two new RAS pumps were then installed with new timers. The regular blockages were from then on eliminated and the clarifier unit performed well.



Photograph 12 Settling tank drain and covers to block out sunrays

10.1.3.8 Waste sludge

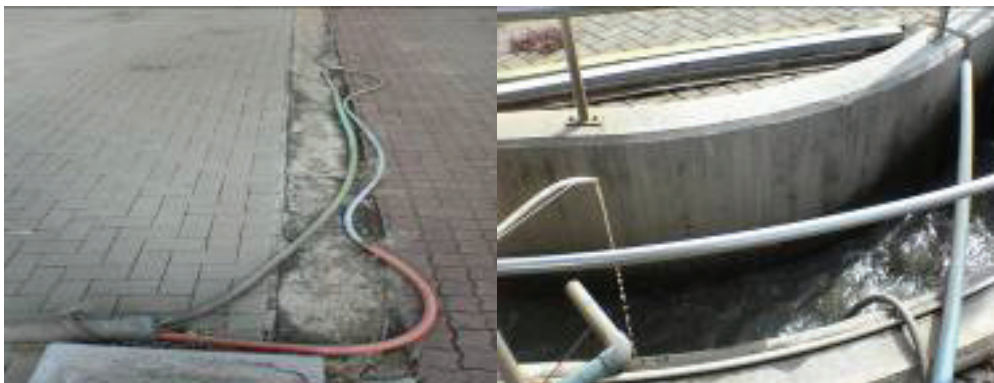
Waste sludge is transferred via a manual valve control from the last tank, by discharging waste sludge directly with gravity feed into the adjacent WCW channel. The settler wastes about 2 ℓ of sludge every 30 minutes; therefore 96 ℓ of sludge is included in the total volume of sludge wasted. Alternatively sludge can be wasted directly from the settler bottom outlet. This line is flushed on a daily basis, with the sludge returned to the anaerobic zone, to ensure blockages do not occur in the bottom of the tank. Refer to Photograph 13.



Photograph 13 Sludge waste points.

10.1.3.9 Effluent outlet

The settling tanks outlet is directed via flexible house pipes to an adjacent WCW drain. Other discharges from the pilot plant enter the adjacent wastewater channel. Refer to Photograph 14.



Photograph 14 Effluent and drain outlets

10.1.3.10 Compressed air supply

A constant supply of compressed air from an existing auxiliary compressor was available, controlled at 5 to 7 bar supply, with a throttle valve and a rota meter (Dwyer instruments), calibrated from 0 to 100 lpm.

After an initial compressed air supply failure, air supply has been constant and 100% available. The air supply pressure has been restricted to 1 bar with pressure control valves. Auto drain valves were installed to purge the condensed water from the supply line, which collected water due to the long pipe transfer length of about 500 m.

The moist compressed air initially damaged the air control valves in the automated DO concentration control system. An additional water trap, together with an automated timer driven drain, has been installed. The pressure control valve drains are also kept slightly open to ensure water drainage. Refer to Photograph 15.



Photograph 15 Air inlet control and air water traps

10.1.3.11 Tank air distribution

Air is distributed into each tank via a Nopol PIK 300 rubber membrane disc diffuser, as indicated in Photograph 16. Air is spread into small bubbles in a size range of between 1-3 mm when released. The efficiency of the diffusers at 0.5m immersion depth, at higher than the recommended air pressure, was sufficient to keep the DO concentration levels in the tanks homogenous and constant.



Photograph 16 Nopol disc with support frame and inlet pipe

Each diffuser has a manual control valve. The distribution of air was however not uniform between tanks, and the supply line had to be changed into a loop, to ensure equal pressure air distributed to all tanks.

10.1.3.12 Tank air control

The DO concentration meters set point was designed to be kept constant by a control valve, which became defective due to water ingress from the supplied compressor air. Solenoid valves were then installed to control the air supply on an open-close basis according to a chosen DO concentration set point in the last 3 tanks. The first 3 cyclic aerobic tanks were aerated via timer control, alternating with the mixer functions of the next 3 tanks. A second DO meter became available for the first three tanks, to control the DO concentration similar to the last 3 tanks.

10.1.4 Monitoring and control systems

10.1.4.1 RAS timer control

The original manual hydraulic sludge height control did not function due to variable inflows at that stage. This was changed to an automated solenoid valve timer controlled transfer sequence, to open and close the drain pipes, which was also unsuccessful due to solenoid valves blocking due to sludge ingress into the valve parts.

The RAS control was then further automated using a timer controlled pump system, with a timer setting of 0 to 18 seconds on and 0 to 15 minutes off. The pumps could not function on the timers and failed on overheating protection due to stop start cycles. The pumps were then set on continuous duty with recycle control and later on continuous duty without recycle control, but they still blocked and malfunctioned. The pumps were then replaced with peristaltic pumps from abandoned samplers, but these pump motors were subsequently damaged due to over current supply.

The RAS control was then changed again with different timers, with timer settings of seconds, minutes, and hours available. A timer setting of 48 seconds on (ensuring enough time for all fibres to be pumped out of pump impeller casing) and 12 minutes off, for a s-recycle ratio close to 1, was successful to prevent further blockages, although it lead to RAS surges during pumping. The high ratio also ensured that the residence time of the sludge in the settler was low, to avoid the problem of rising sludge due to denitrification.

10.1.4.2 Dissolved oxygen concentration meters

The DO concentration meter sensor was moved from last to second last aerobic tank, due to space restrictions from the MLSS concentration meter in the last tank. A mixer was included to ensure the MLSS reading and ACCV meter was collecting a homogenous mixture, even when the air supply was turned off. The programmable automated compressed air DO concentration sensor cleaning was set at every hour for 5 seconds. The PLC programmable solenoid valve opened to discharge air, with a manual control valve, for the cleaning sequence.

Automated DO control via a control valve has been discontinued, as it caused numerous problems during commissioning, due to uneven inlet flow and loads, and control valve malfunctioning. Water in the compressed air lines caused internal parts to malfunction. The tanks also overflowed due to too high tank levels from the aerated content. The open-close air supply solenoid valve controls the air supply at a DO set point.

The DO concentration meter readings fluctuated at stages, and it took a while to identify the reason for the reading instability. The liquid flow through reactor drum transfer pipes seems to build up a static charge, which influenced the DO concentration readings at the commissioning phase. The DO concentration meter readings are based on voltage differences between two electrodes, and stray voltage in the liquid will influence the DO reading. By electrically earthing each tank to ground, the stray voltages are eliminated. Previous fluctuations up to 0.5 mg/l disappeared, resolving the problem.

The sensor brackets were bolted to the tank tops, which made removal for regular cleaning laborious. A simple slip on bracket was therefore designed for all sensor and the probes can be easily removed.

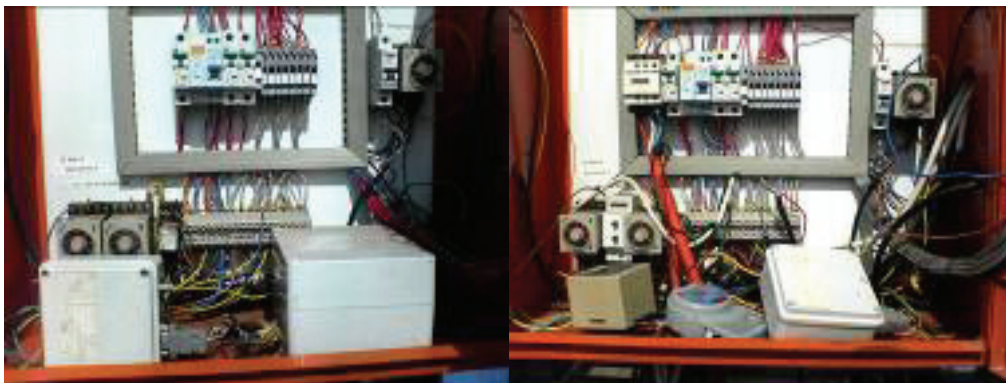
A portable YSI DO meter was available to monitor DO and T readings in all reactor tanks.

10.1.4.3 MLSS concentration meter

One Royce suspended solids meter has been installed and the probe, with long enough power and sensor cables, was interchangeable between tanks. A portable Royce MLSS meter was available for additional MLSS measurements.

10.1.4.4 Data capture

Two data capture units, each capable to capture data in MS and Windows compatible format at variable time intervals, were installed. The one unit logged the settling meter height and MLSS concentration, and the second unit logged the DO concentration. Another unit captured the settling and compression speed, as well as the settling speed, which is transmitted continuously to an office PC. Refer to Photograph 17.



Photograph 17 Pumps timer controls and data capture units

The settling meter data logger readings fluctuated around the expected reading. As the meter sensor is stable, and the output was confirmed as such, it seems as if the loggers were picking up signal spikes at about 0.08mA, leading to a slight reading instability.

It is important that all samples should be as representative as possible.

10.1.4.5 Air control

A PID controller was installed to control the DO concentration in the aerobic tanks at a set point (range 0 to 10 mg/l) of 2.5 mg/l. This system was not functional due to control valve

failure from air moisture ingress, and it was modified with a basic solenoid control valve installation on the air supply line for on off control at any DO set point.

10.1.4.6 Mixing turbulence

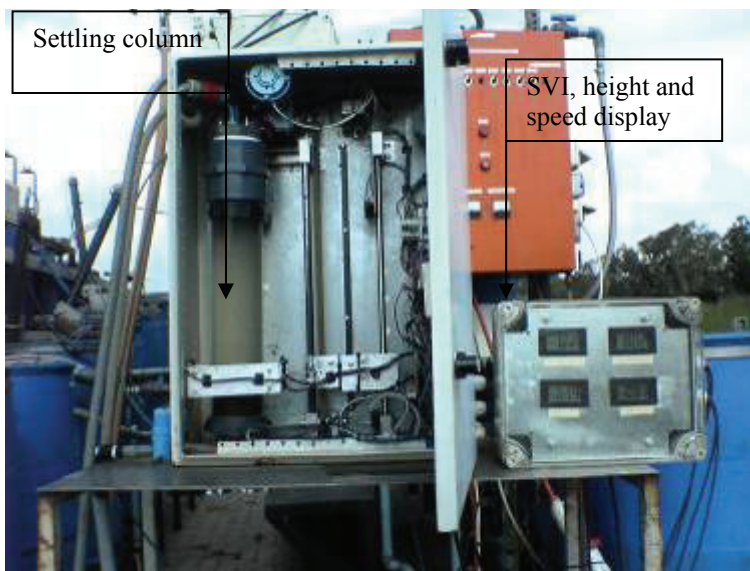
The pumps used in tank 2 and 11 as mixers to keep tank content in suspension, did not operate properly. Specifically in tank 11 (the last tank before the settling tank), the floc break up is visible due to the high turbulence from the pump impeller action. Mixers were installed with a gentle action to ensure flocs do not disintegrate due to excessive turbulence.

10.1.4.7 Temperature control

Due to the small size of the tanks, excessive heat loss means that the minimum temperature in winter reduces to below 10°C, with maximum temperature of about 25°C in summer. One 1.0 kW immersion heater probe was supplied for test purposes, and it is used to increase the temperature in train 1 by about 3 to 5°C.

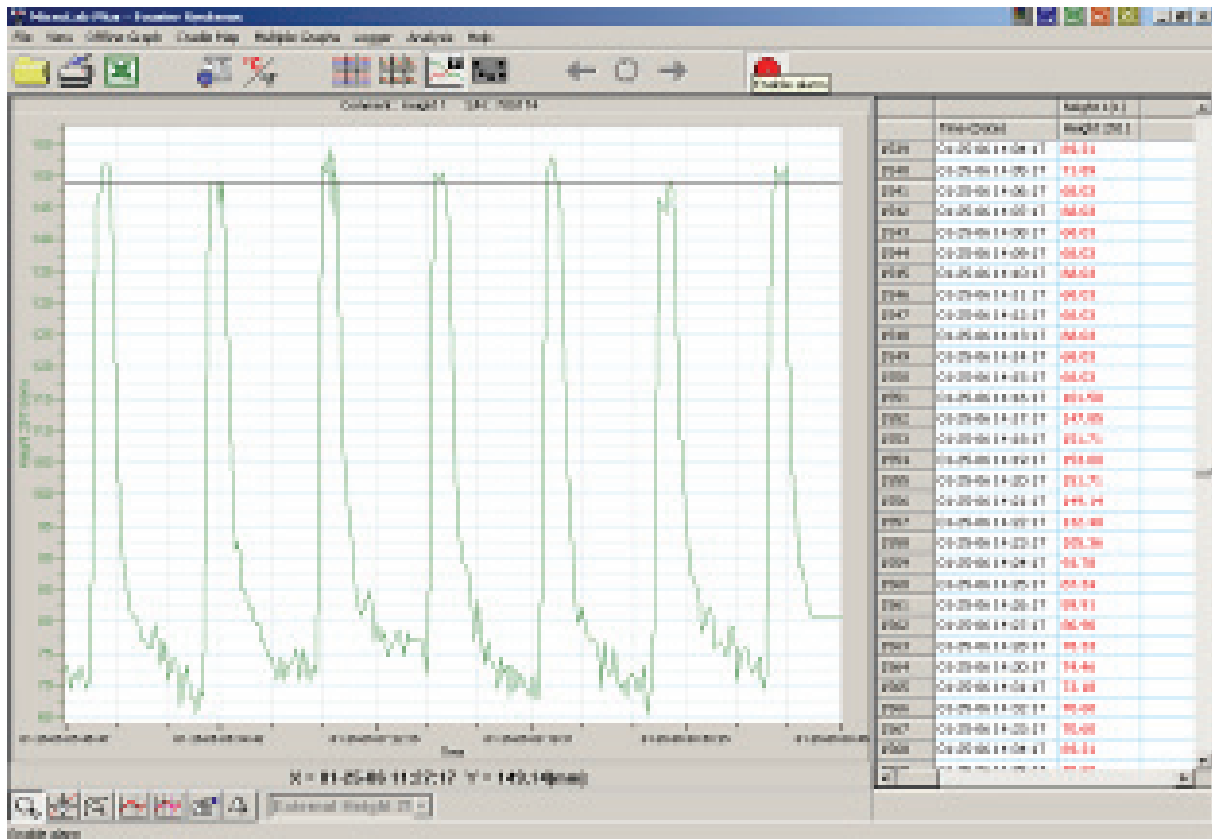
10.1.5 Activated sludge settling velocity meter

Two private companies were approached in 2002 to develop a basic sludge settling monitoring meter. The feasible concept designs were based respectively on (i) fixed column vertical light receivers with a moving light source, and (ii) a moving single point sensor and receiver. The first design prototype unit manufacture was abandoned due to time constraints. The second unit was manufactured as working unit, and it was upgraded a few times. The major modification to the meter was to transfer a sample under vacuum into the settling column, thereby eliminating the original need for gravity supply. The 1 l column was replaced with a 2 l column to prevent or reduce the influence of wall effects on the floc particles during settling. Refer to Photograph 18 for a general arrangement of the meter components.



Photograph 18 MLSS settling meter and output display

Trending data is captured by a 24 hr circular chart or a two-channel data logger. The logger enables transfer and trending in an Excel spreadsheet. With the MLSS meter reading transfer, on-line SVI is determined (with the SV_{30} availability). Refer to Photograph 19.



Photograph 19 On-line 30-minute sludge settling curves from settling meter

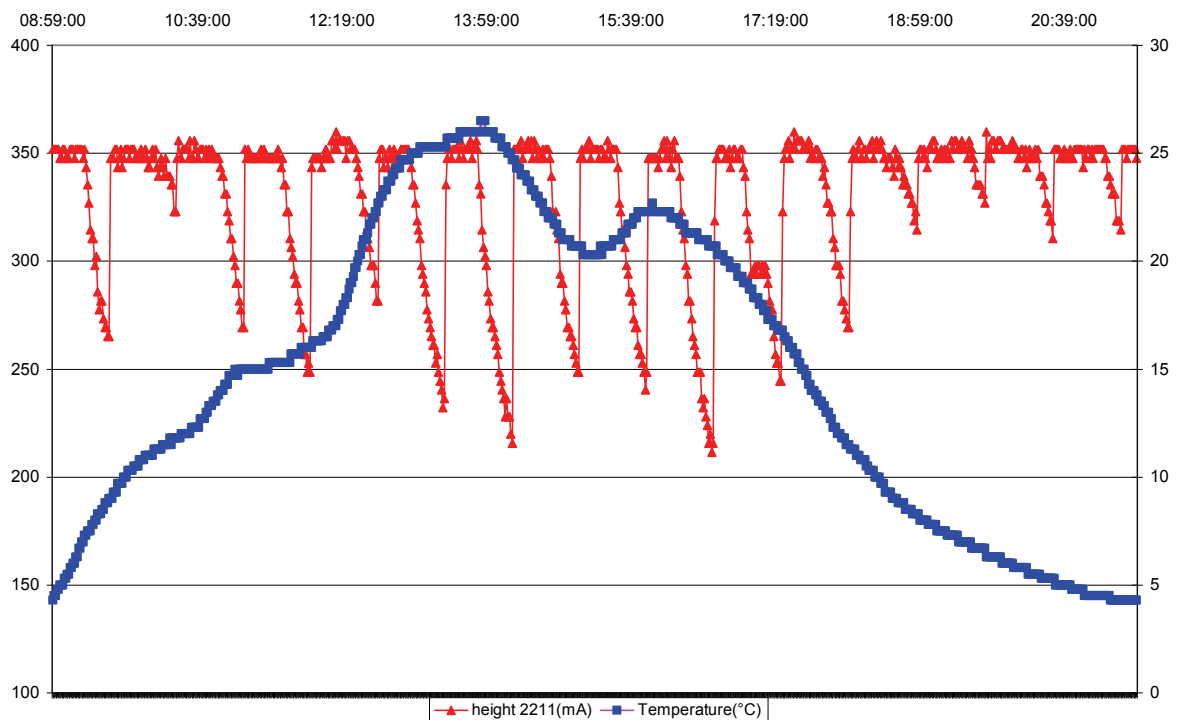


Figure 10-2 Typical settling curves from settling meter and T_r , exported into Excel spreadsheet

The settling meter is one of the main experimental tools for activated sludge settleability monitoring and long-term (one-year) on-line use demonstrated its use and general applications, without any major malfunctions.

10.1.6 Experimental periods

The pilot plant experimental period lasted from May to July 2006. The full-scale on-line MLSS settling evaluation took place in October 2006

10.1.7 Analysis data gathered

10.1.7.1 Parameters

All chemical and most physical parameters measured were in accordance with the standard methods (APHA, 1998). These routine tests were performed at ERWAT Laboratory Services.

The experimental set-up was planned to allow for regular sampling. The different parameters analysed on-site and at the laboratory included, using the classification of Kiely (1998):

- Physical
 - Suspended solids (SS) measures the organic and inorganic suspended solids
 - Temperature (°C) measures the warmth of the sample or the ambient temperature
 - pH (-) measures the alkalinity or acidity of the sample
 - SVI (ml/g) measures the volume of 1 g of sludge after 30 minute settling
 - Turbidity measures the scattering and absorption of light by suspended solids (Droste, 1997)
- Chemical: organic
 - COD
- Chemical: inorganic
 - Total Kjehldal nitrogen
 - Ammonia
 - Total phosphate
 - Orthophosphate
 - Alkalinity
- Microbiological
 - Bacteria population
 - Protozoa
 - Floc form

10.1.7.2 Field data

10.1.7.2.1 Plant flow rate

The flow rate to the pilot plant was measured daily by measuring the time required to fill a 1 l graduated cylinder. The line was flushed and drained, to ensure the flowrate is not restricted due to pipe deposits.

10.1.7.3 Sludge data

10.1.7.3.1 SVI

The SVI procedure is outlined in APHA (1998). MLSS with a known TSS is mixed and placed in a 1 ℓ or 2 ℓ cylinder. The larger cylinder is preferred to minimise bridging of sludge flocs and wall effects (Droste, 1997). The sludge is allowed to settle for 30 minute, and the settled volume of sludge is read after successive settling intervals. The sludge volume after 30 minutes is used to calculate the settled sludge volume.

10.1.7.3.2 Hindered settling velocity

The height of MLSS to liquid interface was recorded at intervals of one minute over the first 10 minutes, every 2 minutes over the next 10 minutes and every 5 minutes over the last 10 minutes.

10.1.7.4 Supernatant data

10.1.7.4.1 Sample taking

Two 10 ml transfer pipettes were used to draw a sample about 10 cm from the top of cylinder. The sample was carefully extracted so that the settled sludge is not disturbed.

10.1.7.4.2 Turbidity

The turbidity analyses on the manual batch samples were performed with a spectrophotometer (Merck Spectroquant). Measurements are expressed in FNU (Formazin Nephelometric Unit), measuring scattering infrared light from a light emitting diode (LED) at a wavelength source of 860 ± 60 nm at an angle of $90 \pm 2.5^\circ$ to the incident light beam. The more familiar NTU (Nephelometric Turbidity Unit) turbidity measurement uses a white light. Clarifier supernatant was collected to observe the pilot plant performance. A 1 ℓ sample was collected with two 10 ml automatic pipettes.

The turbidity was not correlated with the suspended solids during the experimental evaluation. It has been reported that there is reasonable relationships between turbidity and suspended solids of the clarified effluent (Tchobanoglous et al., 2003; Droste, 1997). The measuring principle of on-line biofloc particle size meters are based on light scattering (de Clercq et al., 2000), which is the same principle used for MLSS concentration measurements.

10.1.7.4.3 Ortho-phosphate

The ortho-phosphate analyses on the manual batch samples were done on-site using a spectrophotometer (Merck Spectroquant) and the relevant test kit (Cell Test 14543, 0.05-5.00 mg/ℓ $\text{PO}_4\text{-P}$).

10.1.7.5 On-line monitoring sensors

10.1.7.5.1 Dissolved oxygen concentration

The aerobic reactor DO concentrations were measured with two on-line (Royce Model 9100D) analysers, with an automated timer controller air cleaning. Additional measurements were taken daily using a handheld meter (YSI, Model 550A). Meters were calibrated previously according to the equipment instructions (Royce, 1999). Automated jet clean systems were used to ensure the sensors stayed clean. Meters were removed from the tank every day for rinsing and inspection. The DO concentration meter sensors were immersed at a depth of about 1 m below the surface.

A quick response time was required for the DO concentration control, to prevent large variations in the reactor DO concentration due to slow response control. The standard 2 mm thick membrane was therefore replaced with a 1 mm thick membrane.

10.1.7.5.2 Temperature

The aerobic reactor temperature was measured with two on-line DO (Royce Model 9100D) analysers. Additional measurements were taken daily using a handheld digital meter (Testo). The on-line equipment was calibrated previously according to the instructions indicated.

10.1.7.5.3 MLSS concentration

The MLSS concentration was measured on-line with a Royce meter (Model 7011A), with an automated timer controller air cleaning. Additional measurements were taken daily using a Royce handheld MLSS concentration meter.

The equipment was calibrated previously according to the instructions (Royce, 1999) indicated. The automated sensor jet clean system was used to ensure the sensor stayed clean. The meter was removed from the tank to wash and inspect the sensor about every third day. The MLSS concentration meter sensor was immersed at a depth of about 1 m below the surface to ensure a representative reading.

10.1.7.6 Quality verifications

A verification procedure was introduced to ensure consistent measurements by the sensor equipment. The cleaning cycle of the DO and MLSS meter was increased to ensure clean sensors. The DO and MLSS absolute values were checked with portable meters. The meters were calibrated once a month.

10.1.7.7 Data statistical procedures

Data loggers' data was stored downloaded in MS Excel format, and the available Excel statistical analysis tools were used to calculate all the relevant settleability criteria.

The DataFit (2005) statistical package was used to evaluate the non-linear multivariable relations. MLSS and T were the fixed variables, and SVI, SV_{30} , t, u_{max} , u_{ave} , u_1 , u_2 , u_3 , u_4 , u_5 and u_6 were the variables. Linear regression was used to obtain statistical relationships.

Fluctuations in regressions were evaluated based on the coefficient of variability (R^2). This statistical parameter is used to compare the different sets of data when the mean differs considerably (DataFit, 2005).

10.1.7.8 Operational procedures

The control strategy of the pilot plant was to simulate BNR, and to suppress flow and load variations. In principle, a constant feed was required, but there were still variations in the inflow that could not be controlled precisely.

Table 10-1 Control items regulating conditions during experimental work

Control item	Control method	Setting value	Measuring item	Measuring point
Air flow rate	Constant DO control	2 mg/ℓ	DO concentration	Reactor outlet
Inflow	Height	ca. 10 s/ℓ	Inflow	Discharge point
a-recycle	Timer	On-off	Flow rate	Discharge point
Tank content	Waste 0.5 of content	2 d sludge age	Level meter	Tank Float

10.1.7.9 Operational Performance

10.1.7.9.1 Seeding

The WCW RAS stream was used as an inoculum (approximately 100 ℓ/start-up) to supply about 10% volume to seed the pilot plant for each start-up. Dissolved air flotation (DAF) thickened sludge was later used, as this reduced the required volume by about ten-fold.

10.1.7.9.2 Operation

It was proposed to run two identical pilot plants in parallel. The requirements for comparability posed high operational demands, and small changes such as inflow rate variations made comparisons very difficult.

The plant has been operational for a few periods for up to 1 month at a time. After all equipment failures have been resolved, the pilot plant was started up on 11 May 2006, and it continued to be operated until the end of August 2007.

10.1.7.9.3 Operational problems

The most important aspect of the pilot plant was to create steady state conditions to ensure settleability variations are properly monitored.

10.1.7.9.4 SRT and Flow control

The pilot plant flow could not be sustained continuously over the experimental period. Several incidents of blockages occurred which were removed during the daily inspections.

Table 10-2 SRT and HRT for pilot plant

	HRT [hr]	SRT [d]
average	16	16
max	100	22
min	8	2
St.dev	10	5
n [-]	82	84

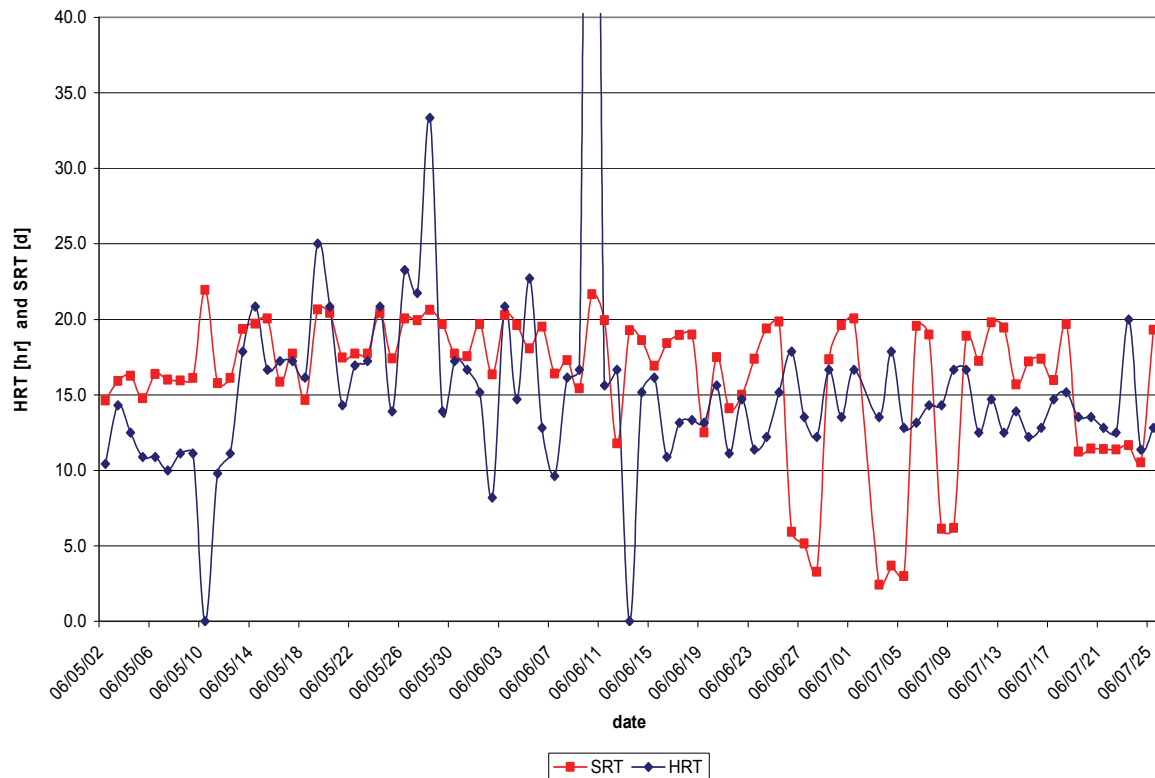


Figure 10-3 Pilot plant HRT and SRT

10.1.7.9.5 DO and MLSS concentration control: pilot plant

The DO concentration control, with the set point of 2.5 mg/ℓ over the period from May to July 2006, controlled the DO concentration to an average of 2.4, with a 0.2 mg/ℓ standard deviation, as illustrated in Table 10-3. Short-term instances of zero DO concentration conditions occurred due to air blower failure or power trips.

Table 10-3 DO and MLSS concentration data for pilot plant

	DO [mg/ℓ]	MLSS [mg/ℓ]
Average	2.4	3841
Max	6.8	5027
Min	0.0	1235
St.dev	0.2	561
n [-]	15493	15493

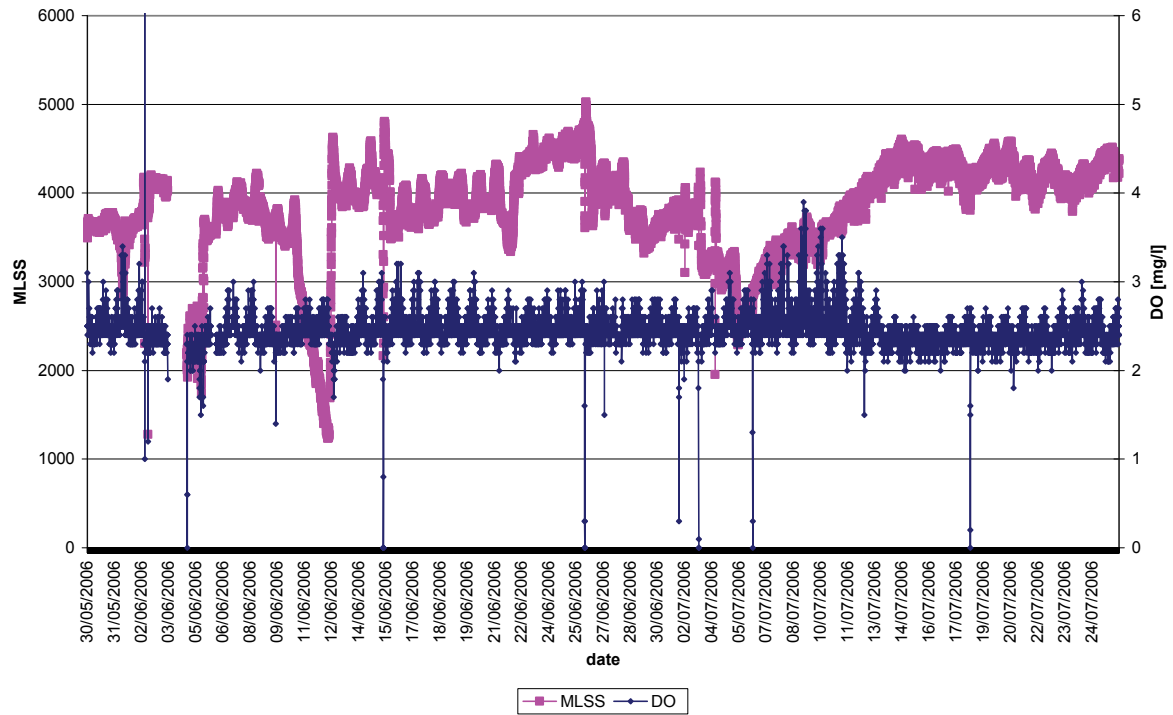


Figure 10-4 Pilot plant DO and MLSS concentration

10.1.7.9.6 DO and MLSS concentration control: full-scale

Although the MLSS should have been constant over diurnal periods, there were still variations in MLSS concentration. The raw sewage feed into the pilot plant tank 1 changed, causing a variation in the pilot plant reactor loading.

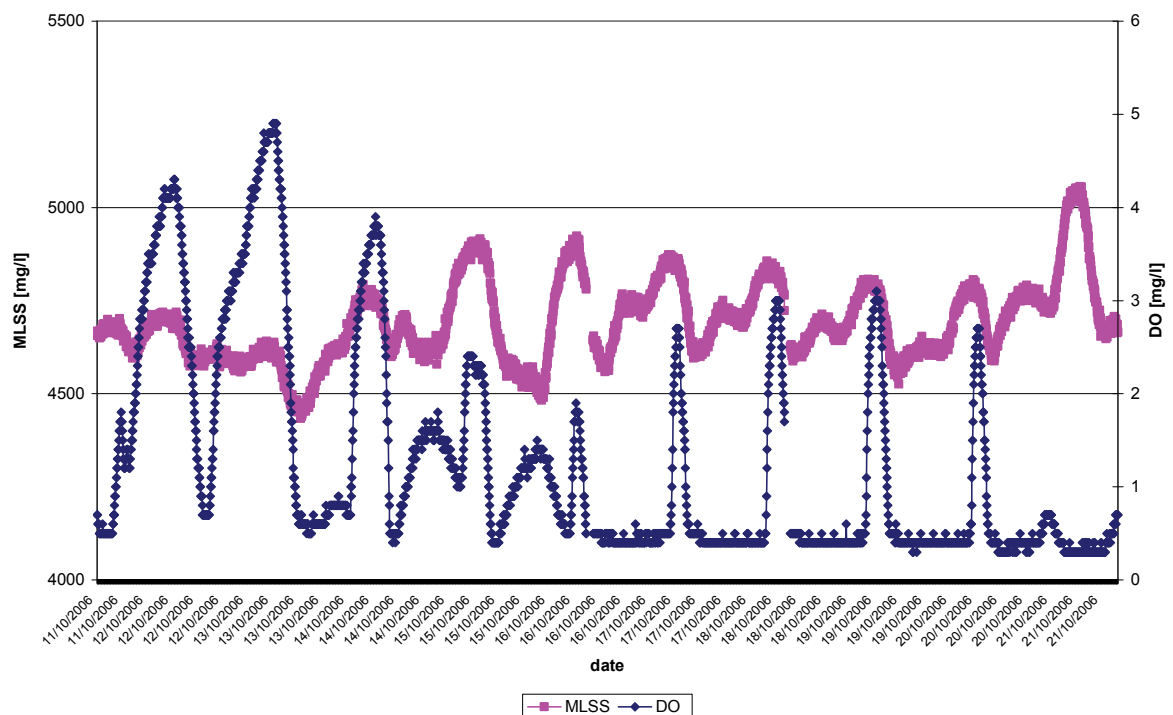


Figure 10-5 WCW DO and MLSS concentration

Table 10-4 DO and MLSS concentration data full-scale

Date	DO [mg/l]	MLSS [mg/l]
Average	1.4	4762
Max	4.9	5435
Min	0.2	3398
St.dev	1.2	165
n [-]	4503	4503

10.1.7.10 Wastewater characterization

10.1.7.10.1 Introduction

The following section provides a brief overview of the WCW raw sewage supply and settled sewage changes, nutrient ratio and VFA generation.

10.1.7.10.2 Raw sewage

The raw sewage did not contain any heavy metals that are toxic or inhibitory to MLSS. A summary of the most important constituents is listed in Table 10-5 .

Table 10-5 Raw sewage and final effluent, pilot plant

		raw			final			removal
		ave	stdev	n	ave	stdev	n	
pH	[-]	7.2	0.2	67	7.6	0.2	67	
Cond	[mS/m]	107	29	67	90	33	67	
COD	[mg/l]	1188	326	67	56	34	67	95%
NH3	[mg/l]	35.5	4.5	67	16.2	12.6	67	54%
NO3	[mg/l]				4.2	3.1	67	
TKN	[mg/l]	75.8	12.9	34	22.2	16.2	32	
oPO4	[mg/l]	9.3	1.4	67	0.6	1.4	67	93%
TP	[mg/l]	14.8	2.3	34	2.0	2.0	34	
SS	[mg/l]	397	140.8	67	20	22.5	67	95%
Talk	[mg/l]	312	38.8	67	240	61.1	67	

Table 10-6 Raw sewage constituents

	SO4 [mg/l]	Cr [mg/l]	Cu [mg/l]	Ni [mg/l]	Pb [mg/l]	Zn [mg/l]	Fe [mg/l]	Cd [mg/l]	Mn [mg/l]	Na [mg/l]	Al [mg/l]
ave	104	0.05	0.07	0.11	0.21	0.30	2.12	0.04	0.25	84	1.3
stdev	12	0.03	0.04	0.08	0.10	0.16	0.93	0.00	0.08	20	1.0
n	32	34	34	34	34	34	34	34	34	30	34

10.1.7.10.3 Raw and settled sewage

In the raw sewage storage tank, the suspended solids removal is about 75% and the COD removal about 40%, while the increase in ammonia and ortho phosphate is about 15% and 40% respectively, as illustrated in Figure 10-6.

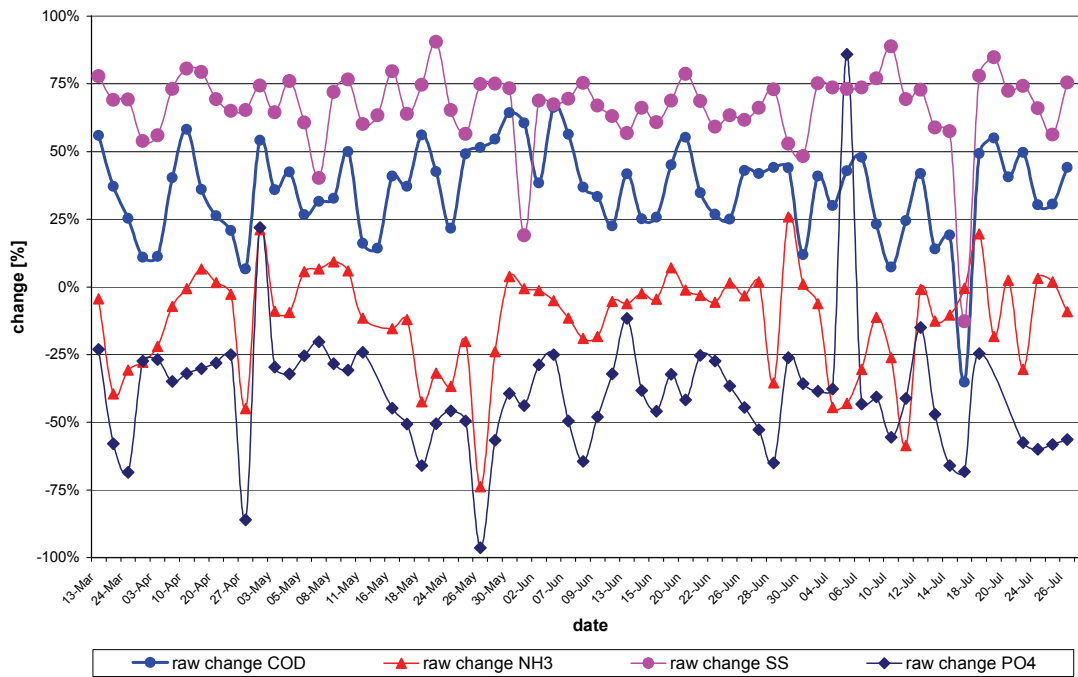


Figure 10-6 Raw and settled sewage feed constituent concentration change

10.1.7.10.4 Settled sewage nutrient ratio

The settled sewage TKN/COD nutrient ratio indicated some variation, at an average of about 0.08 to 0.09, as illustrated in Figure 10-7.

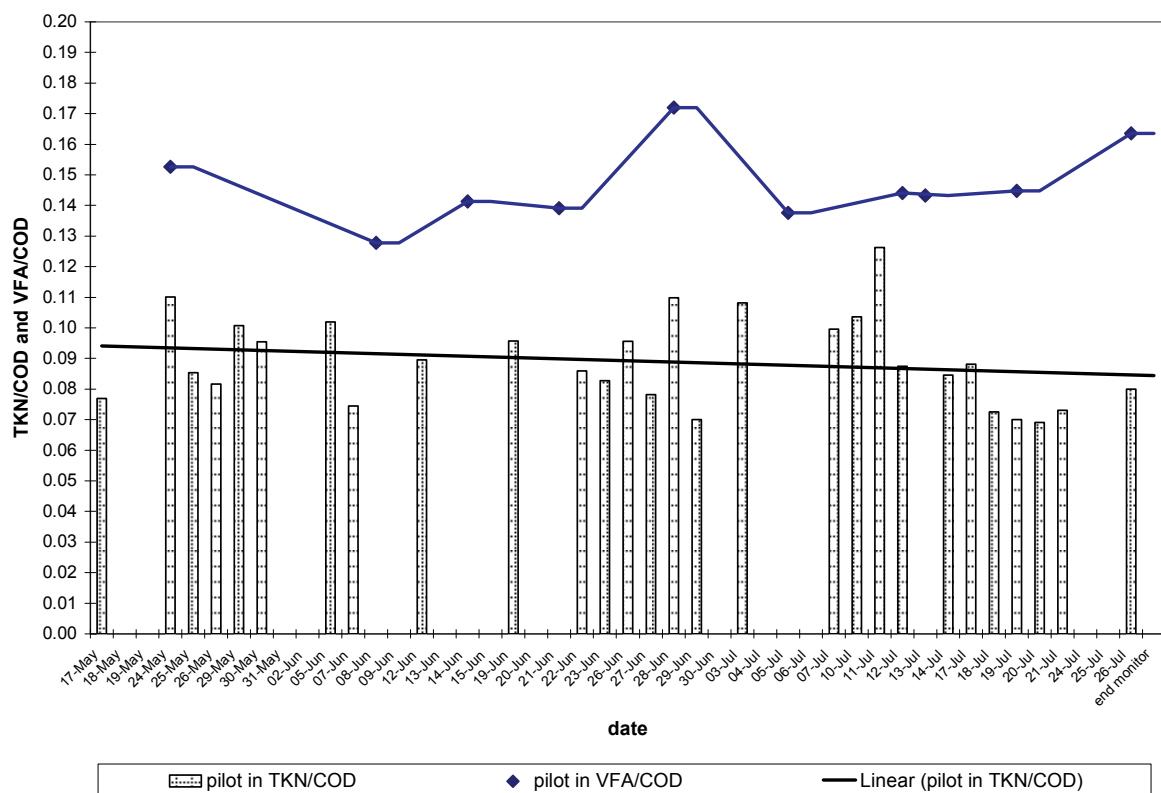


Figure 10-7 Settled sewage feed nutrient feed

10.1.7.10.5 VFA generation

Widespread use of primary sludge prefermentation includes the recycle of generated VFA, to be elutriated from the primary sludge by a wastewater source, as proposed by Barnard (1984). This author researched aspects of VFA elutriation, to ensure the generated VFA is washed out of the sludge into the liquid phase. In this project, sufficient VFA generation was obtained with minimal elutriation in the storage tank, resulting in excellent phosphate removal in the pilot plant. The generated VFA in the settled sludge ascended from the bottom of the tank to the top without the need for additional turbulence or contact. According to Janssen *et al.* (2002), a longer sludge retention time of 40 to 100 hr is required for sufficient VFA production in the lower psychrophilic temperature range (10 to 20°C). These conditions were achieved in the storage tank.

10.1.7.11 Pilot plant performance

The following section provides results of the pilot plant performance, to be used as a reference basis for settleability evaluations. The COD, NH_3 , o-PO_4 , and SS feed and effluent concentrations are summarised, as well as the VFA generated in the storage tank.

10.1.7.11.1 COD removal

Figure 10-8 indicates that the COD in the storage tank feed increased gradually, without affecting the final effluent COD, which was usually below 50 mg/ℓ.

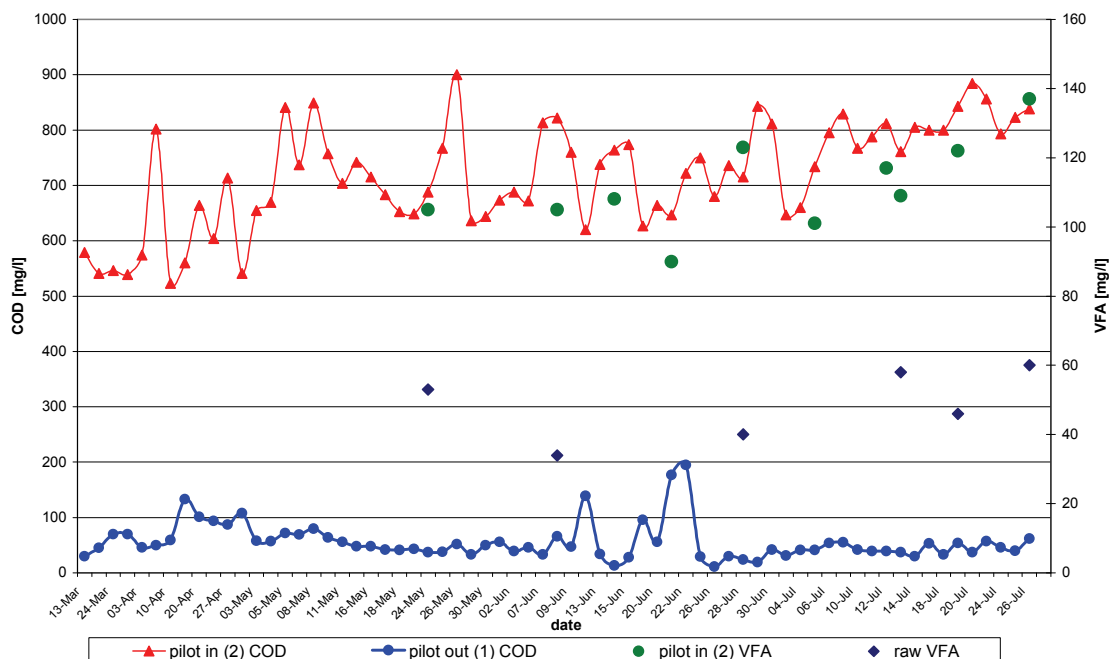


Figure 10-8 COD concentration in feed and effluent, and VFA generation

10.1.7.11.2 NH_3 removal

Figure 10-9 indicates that NH_3 in the storage tank feed varied substantially with concentrations reaching 55 mg/ℓ in cases. Nitrification was lost for periods when sludge wasting for MLSS concentration control decreased the sludge age below the nitrification minimum.

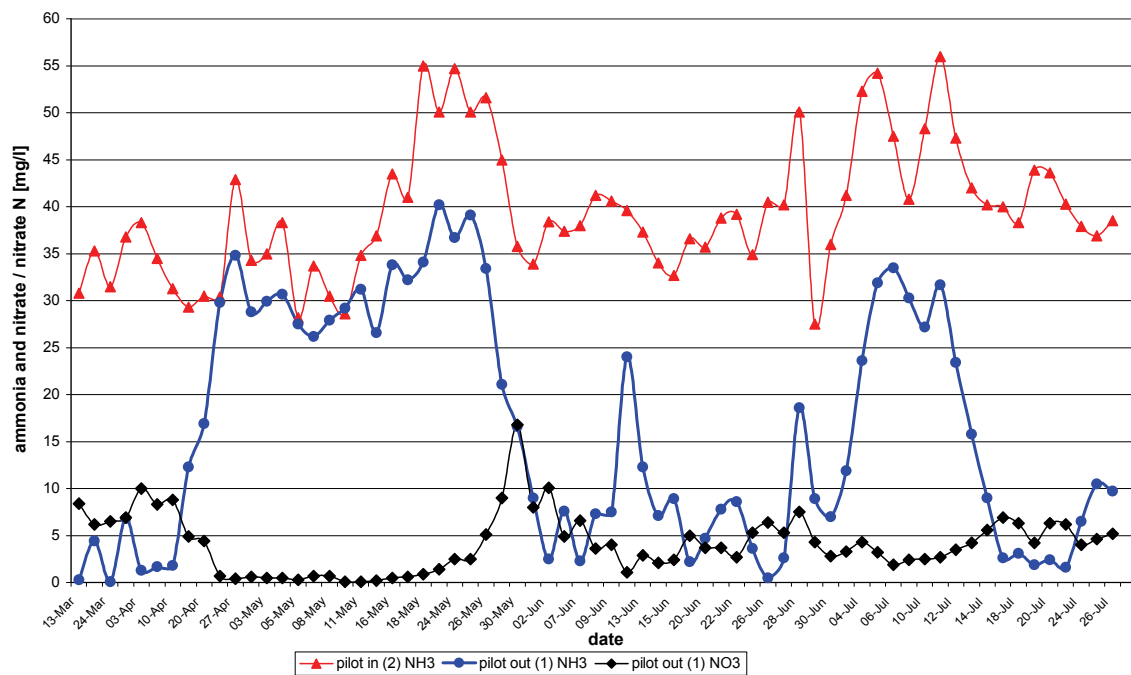


Figure 10-9 NH_3 concentration in feed and effluent, and nitrate in effluent

10.1.7.11.3 P removal

Figure 10-10 indicates in the storage tank feed P increased gradually, without affecting the final effluent P, which was usually below $1\text{mg}/\ell$. The continuous low level of P in the effluent indicates once again the importance of properoxic conditions in the reactor zones.

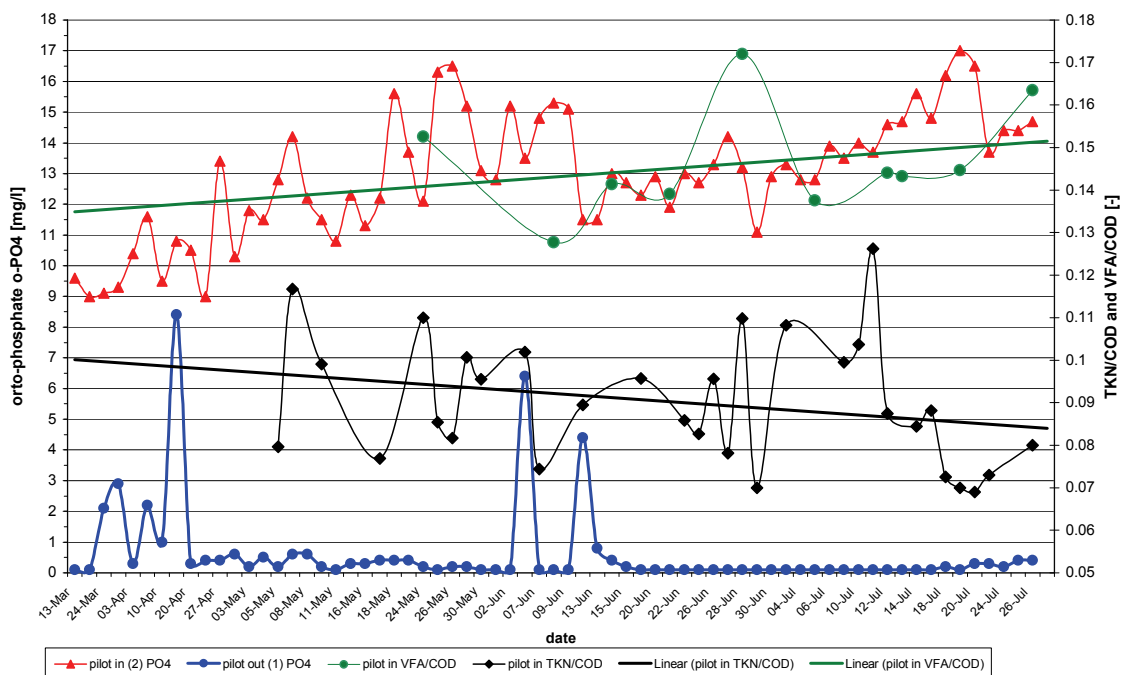


Figure 10-10 P concentration in feed and effluent, and nutrient ratios

10.1.7.11.4 SS removal

Figure 10-11 indicates that the SS in the storage tank feed varied substantially, but SS removal in the final settling tank was not largely influenced by feed variations. The SS concentration is usually below the detection limit of 10 mg/ℓ.

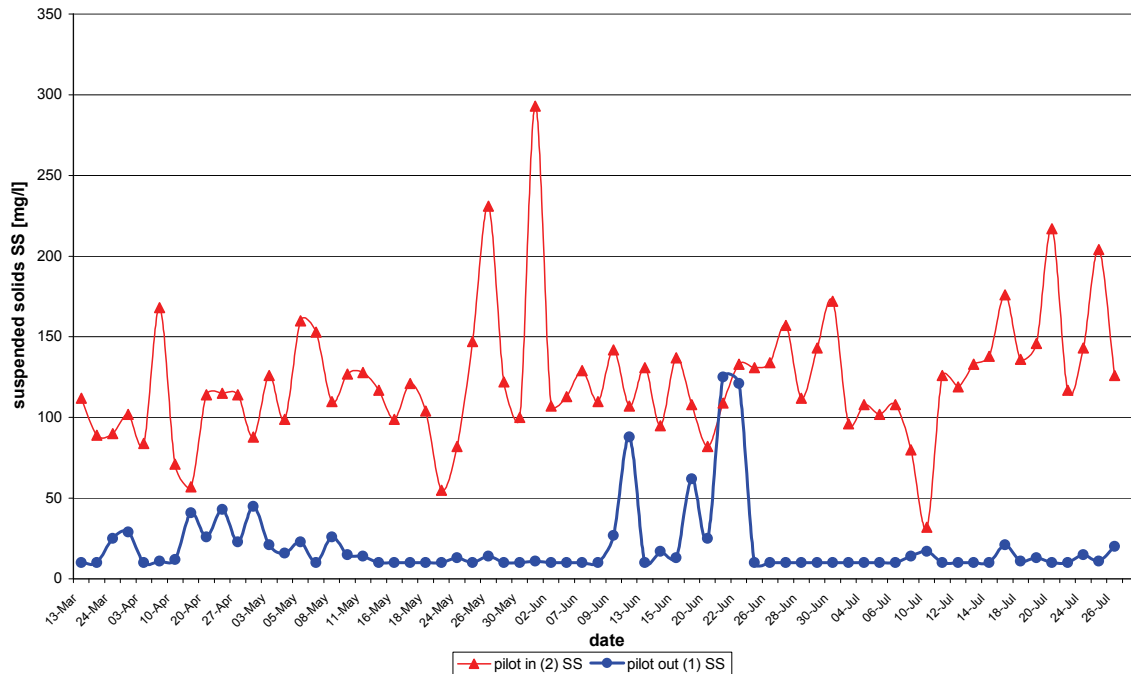


Figure 10-11 SS concentration in feed and effluent

10.1.7.12 Constituent percentage removal

The nutrient removal over the experimental phase is indicated in Figure 10-12.

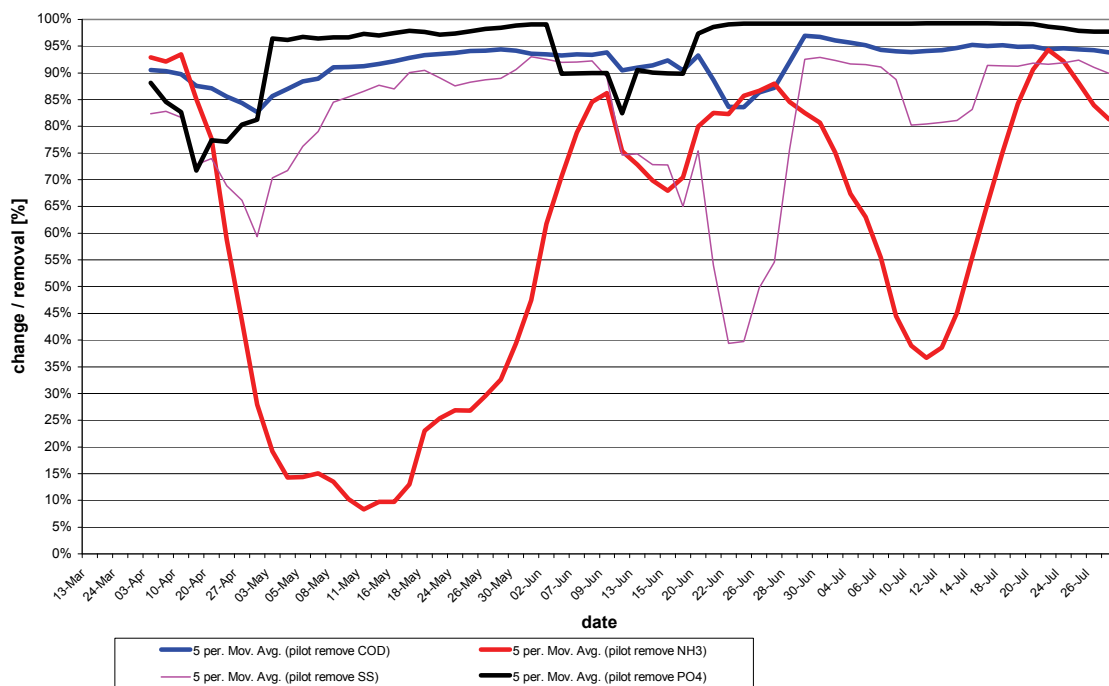


Figure 10-12 Pilot plant COD, NH₃, o-PO₄, and SS removal

The removal of NH_3 was governed by the sludge age changes. The sludge age varied due to MLSS concentration control through sludge wasting. The loss of SS removal was usually due to settling tank RAS pump defects, which also influenced the COD removal. The o-PO_4 removal was the most constant, with deviations due to equipment malfunctioning, usually related to compressed air supply.

10.1.7.13 Microorganisms identification

Standard microbiological surveys were carried out on MLSS samples from the different reactor zones. Special attention was paid to confirm that unfamiliar organisms did not dominate the biomass. Anecdotal information claims that low plant flow conditions, with a large reactor wall surface to volume ratio, as found in small pilot plants, can lead to the proliferation of certain non-mobile bacteria. Controlled experiments are also difficult with wastewater, as the microorganisms change the characteristics continuously (Yuan, 2001). It is therefore important to detect unusual population dominance by unfamiliar organisms.

10.1.7.13.1 Filaments and protozoa and metazoan identified in all reactor zones

The microscopic analysis on the MLSS samples from the pilot plant did not reveal any dominance of unfamiliar organisms. The 33 samples investigated included in 32 instances *M. parvicella* and *Aspidisca* as the most abundant filament and protozoa/metazoa, as summarised in Figure 10-13. *Thiotrix I* and *Vorticella* were respectively identified in 31 and 30 of the 33 samples, followed by Type 0041 and Rotifers in 29 and 28 of the 33 samples. The rest of the organisms are shown in decreasing order of magnitude in the last aerobic reactor zone in Figure 10-13.

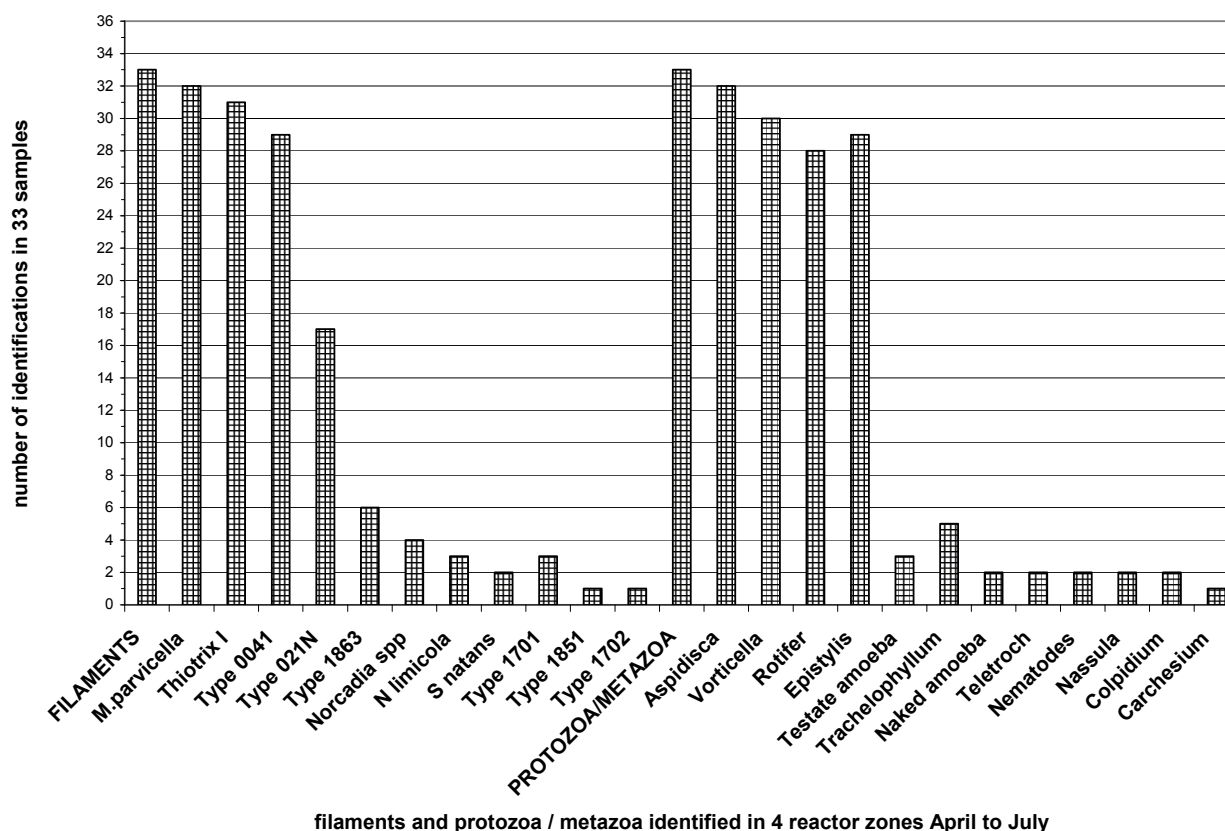


Figure 10-13 Microbiological evaluation of sludge for filaments and protozoa or metazoan

10.1.7.13.2 Filaments and protozoa and metazoan identified in different reactor zones

The microscopic analysis on the sludge samples from the pilot plant reactor zones indicated that the dominant organisms were found in all zones. In Figure 10-14, *M. parvicella* and *Aspidisca* can be seen present in the four zones sampled, which were the anaerobic, anoxic, and start and end of aerobic zone. The other organisms identified follow a similar appearance in the zones. The rest of the organisms are shown in decreasing order of magnitude in the four reactor zones in Figure 10-14.

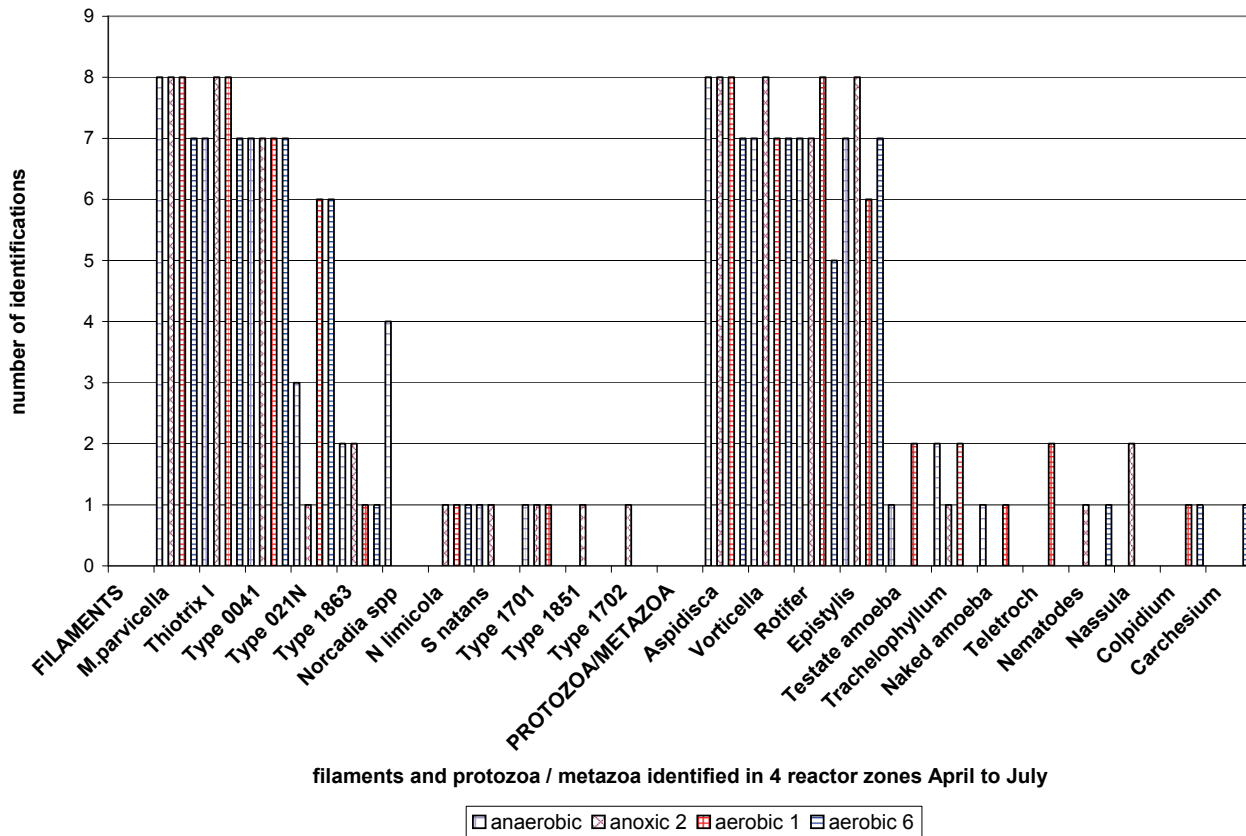


Figure 10-14 Microbiological evaluation of sludge in reactor zones

10.1.7.14 Data gathered

The following section provides results of the typical diurnal profiles for the pilot plant and WCW, to be used as a basis for settleability evaluations. On-line data gathered must be reviewed for its consistency (Bergh, 1996), and extreme values, sudden changes, missing data possible outliers etc. must be part of a preliminary filtering.

10.1.7.15 Diurnal profiles for Pilot Plant

For each 24-hour period, T_r , T_a , MLSS concentration and settling meter height data is stored by the data loggers. Results for 2 July are provided as an illustration of raw data profiles.

10.1.7.15.1 Temperature

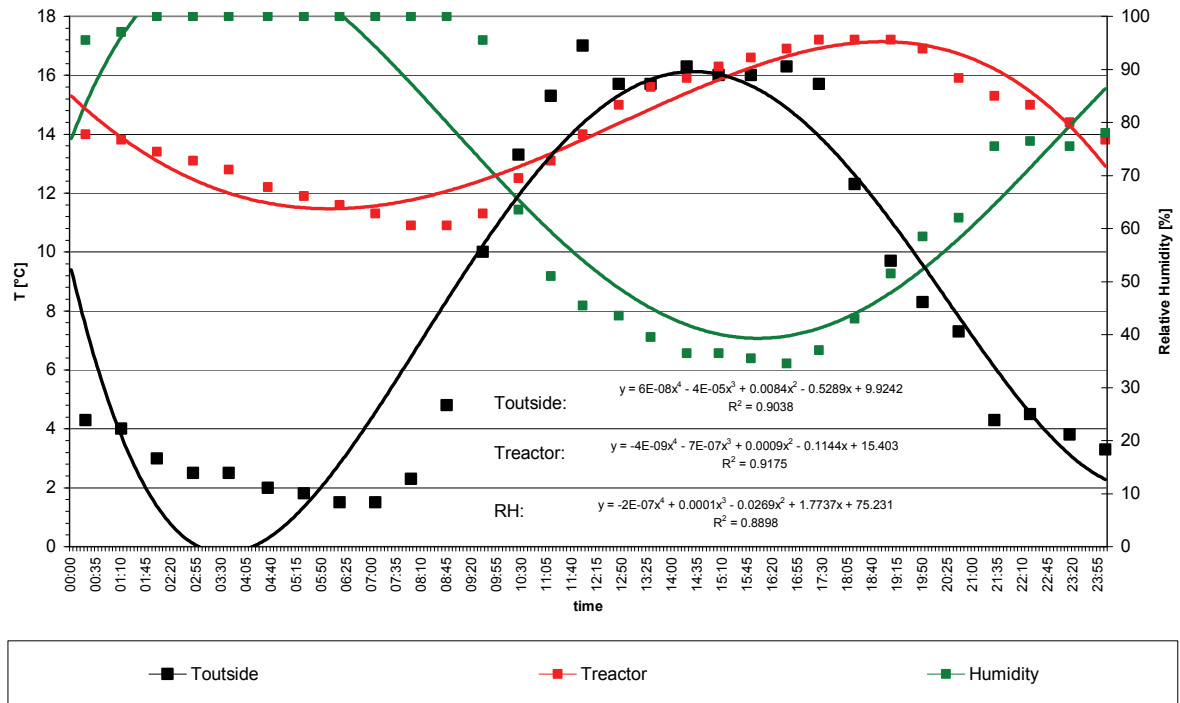


Figure 10-15 Diurnal reactor and ambient temperature and relative humidity

10.1.7.15.2 MLSS concentration

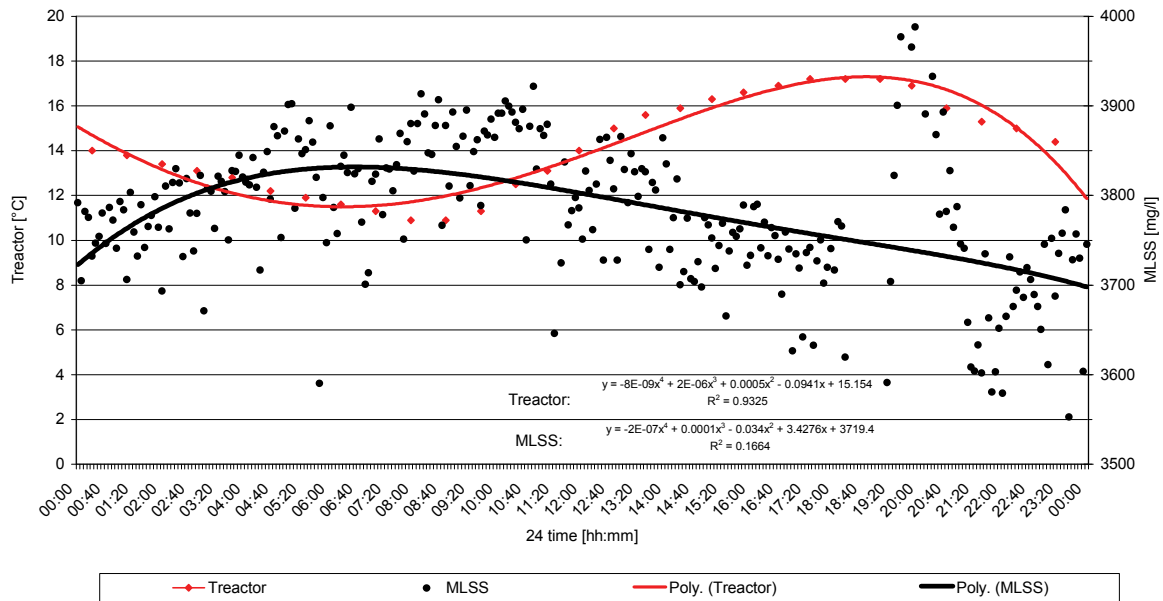


Figure 10-16 Diurnal reactor temperature and MLSS concentration

10.1.7.15.3 h

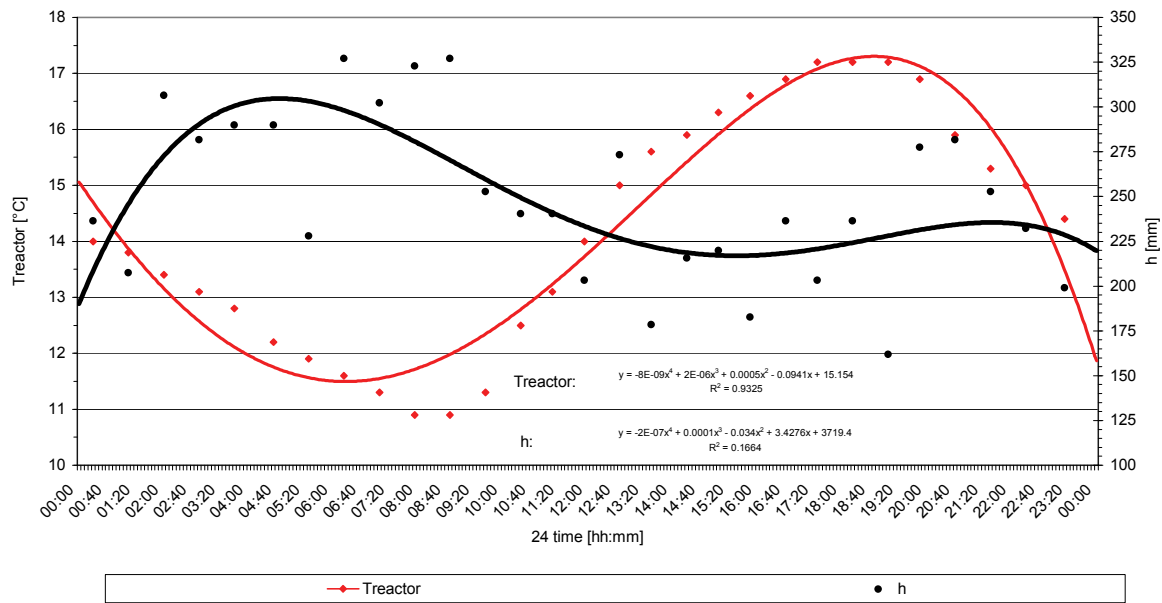


Figure 10-17 Diurnal reactor temperature and settling meter height

10.1.7.15.4 SVI

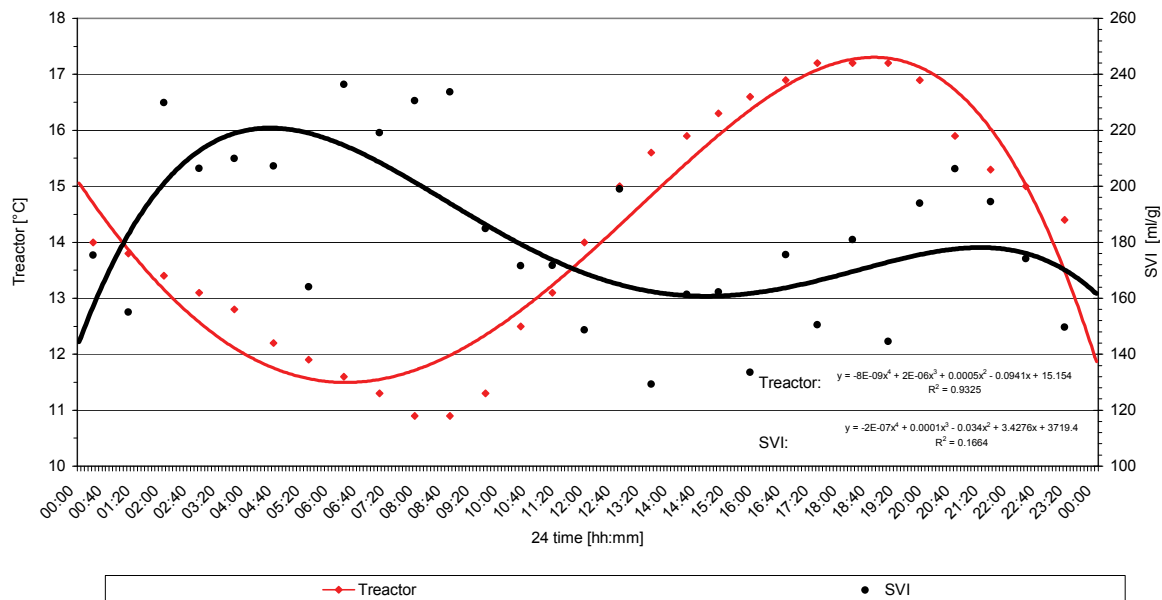


Figure 10-18 SVI related to diurnal reactor and ambient temperature

The ambient temperature varied from 1 to 20 °C on a typical winters day (2 July), creating a temperature variation of 11 to 17 °C in the reactor over a 24-hr period. The SVI is directly related to the reactor MLSS temperature as shown in Figure 10-18.

10.1.7.15.5 Maximum settling velocity

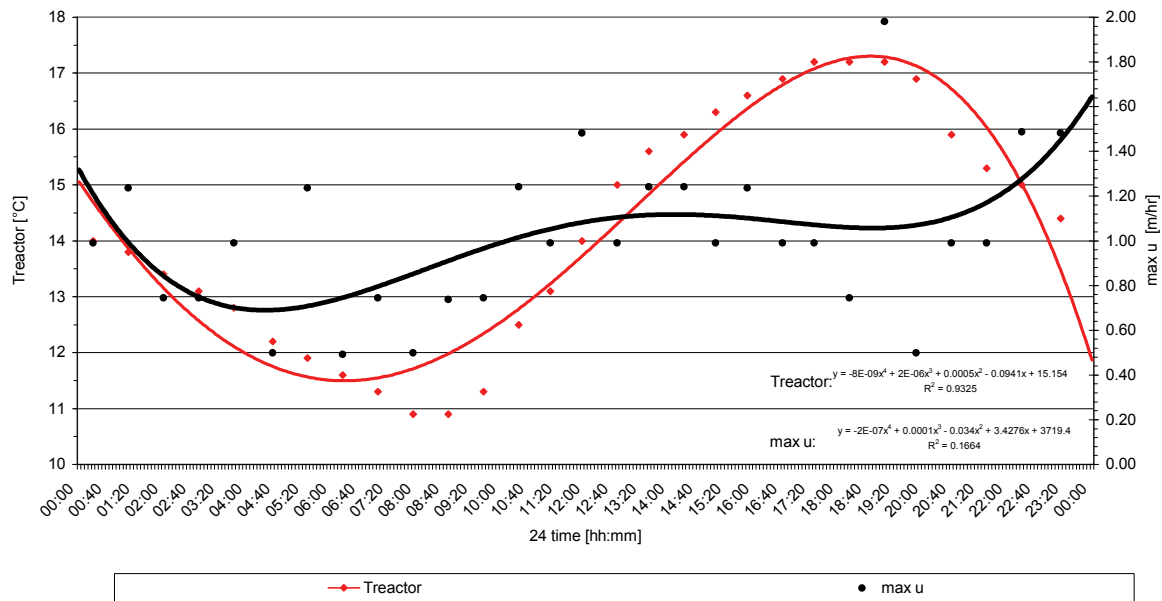


Figure 10-19 Maximum settling speed related to reactor temperature

The ambient temperature varied from 1 to 20°C on a typical winters day (2 July), creating a temperature variation of 11 to 17 °C in the reactor over a 24-hr period. The average settling speed is directly related to the reactor sludge temperature as shown in Figure 10-19 .

10.1.7.15.6 Settleability related to DO variation

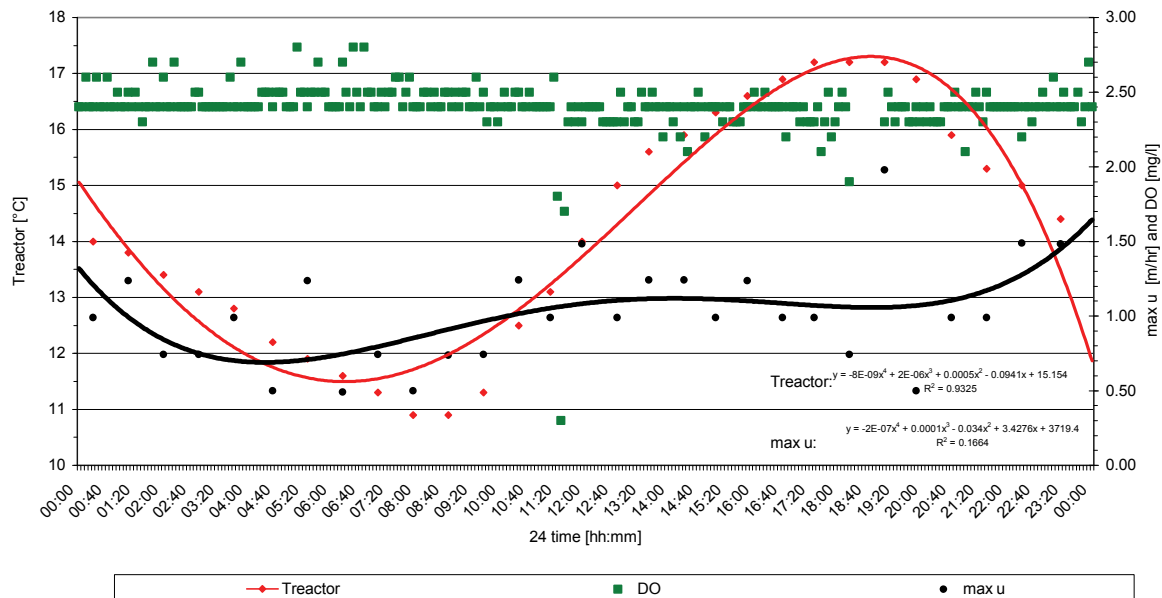


Figure 10-20 Maximum settling speed related to diurnal reactor temperature and DO

There is according to Figure 10-20 no obvious relationship between DO concentration and settleability.

10.2 Appendix A2: Pilot plant operation experimental boundaries

The on-line MLSS meter settling tests produced 354 MLSS settling profiles for the pilot plant. The experimental data range boundaries are listed in Table 10-7. The reactor MLSS concentration and T_r variations at the pilot plant are recorded from 1235 to 4588 mgSS/ℓ, and from 8.1 to 22.2°C. The large T_r variations at the pilot plant are achievable due to the small 220 ℓ size of the reactor tanks, which created a large heat exchange surface area with the surrounding atmosphere at a higher or lower T_a . The large MLSS concentration variations at the pilot plant occur during the manipulation of the SRT by additional MLSS wasting from the reactor.

Table 10-7 Experimental data range for on-line MLSS settling evaluation

Parameter	Pilot plant
n	354
Minimum Temperature T_r [°C]	8.1
Maximum Temperature T_r [°C]	22.2
Minimum MLSS concentration [mg/ℓ]	1235
Maximum MLSS concentration [mg/ℓ]	4588

10.3 Appendix A3: Pilot plant operation, results and discussion

The on-line MLSS settling results from the pilot scale evaluation contain settling parameter diurnal profiles, model fitting of SVI, $u_{\max}$, and $t_{\max}$, followed by correlations between SVI, $u_{\max}$ and $t_{\max}$.

10.3.1 Diurnal MLSS settling meter h and T_r diurnal variation

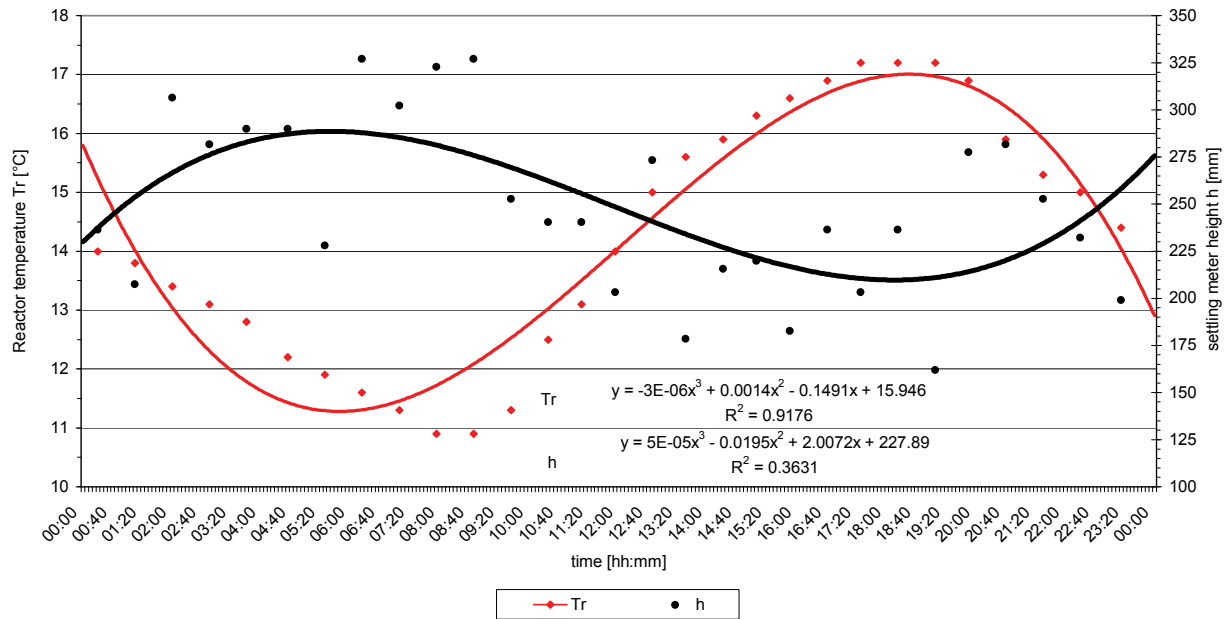


Figure 10-21 Diurnal T_r and settled sludge height variation, pilot

The recorded data points and fitted trends for the diurnal T_r and settled MLSS height variations for the pilot plant were shown in Figure 10-21. The x_1 -axis indicates the 24-hr diurnal period, the primary y_1 -axis indicates T_r , and the secondary y_2 -axis indicates the MLSS settling meter h reading.

The pilot plant T_r fluctuates by about 6.5°C per day in winter. The diurnal profile changes from 10.8 to 17.3°C, and the h profile changes from 325 to 160 mm, as shown in Figure 10-21. Both profiles follow a sinusoidal trend. The MLSS settling meter height reading illustrated the inverse relationship between temperature and 30-minute sludge settling height. The MLSS settling meter h data was more scattered due to unsteady experimental conditions, such as the on-off sequences of air supply for DO concentration control in the pilot plant tanks.

10.3.2 Diurnal MLSS concentration and T_r variation

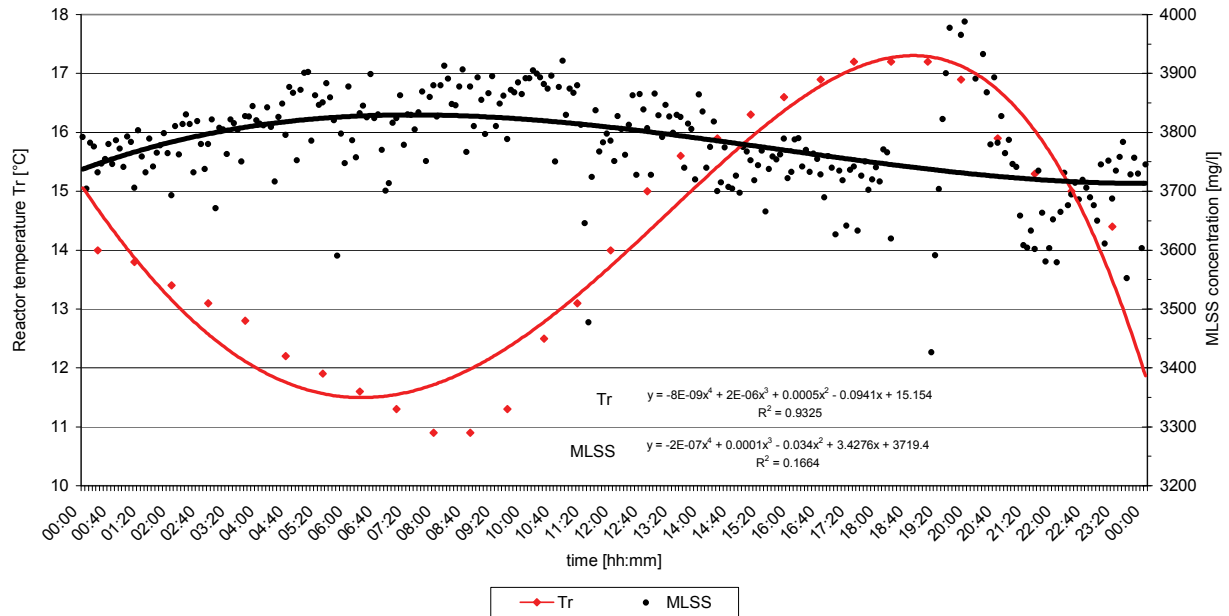


Figure 10-22 Diurnal T_r and MLSS concentration, pilot plant

The recorded data points and fitted trends for the diurnal T_r and MLSS concentration variations for the pilot plant are shown in Figure 10-22. The x_1 -axis indicates the 24-hr diurnal period, the primary y_1 -axis indicates T_r and the secondary y_2 -axis indicates the on-line MLSS concentration reading.

The pilot plant average MLSS concentration varied by about 200 mg/l per day. The MLSS concentration profile over daily 24-hour period followed only a slight diurnal pattern, as the pilot plant wastewater flow rate and solids loading were relatively constant over 24 hours. The scatter of data points in a 100 mgSS/l band could be attributed to the impact of unsteady experimental conditions in the reactor tanks, as well as the temperature impact on the MLSS sensor reading.

10.3.3 Diurnal SVI and T_r variation

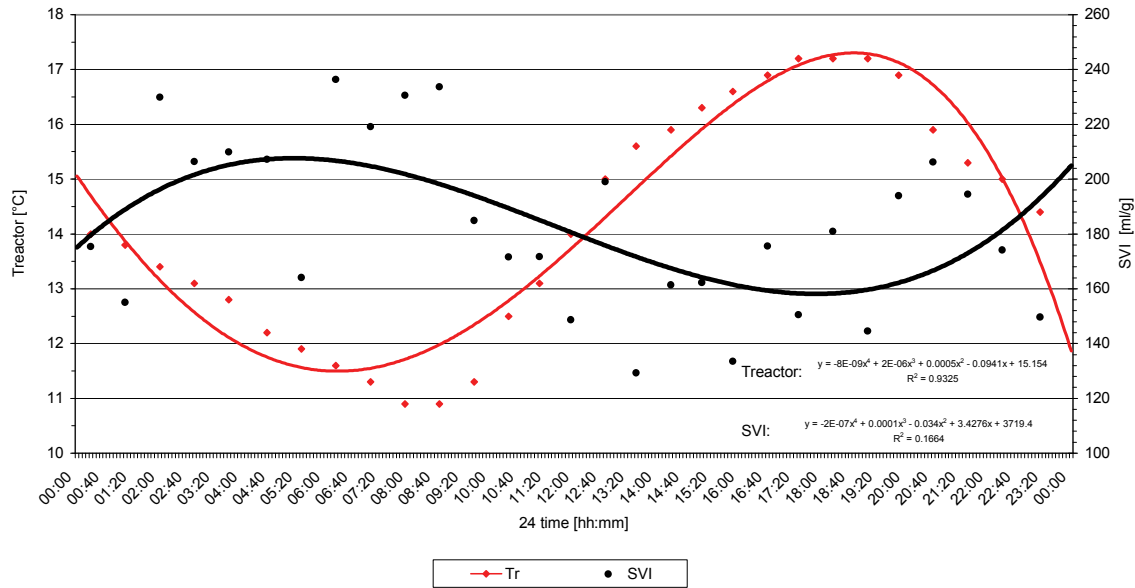


Figure 10-23 Diurnal T_r and SVI, pilot plant

The calculated SVI, recorded data points for the diurnal T_r , and fitted trends for the pilot plant, are shown in Figure 10-23. The x_1 -axis indicates the 24-hr diurnal period, the primary y_1 -axis indicates T_r and the secondary y_2 -axis indicates the calculated SVI reading.

The pilot plant average SVI varied by about 50 ml/g. This variation was caused by the diurnal MLSS concentration and T_r variation. Both profiles follow diurnal sinusoidal trends.

10.3.4 Model fitting: SVI dependence on MLSS concentration and T_r

The correlations that include not only MLSS concentration, but also T_r , produce in all cases improved models with higher R^2 , when compared to the correlations based on MLSS concentration alone. The R^2 for the SVI correlation improved for the full-scale and pilot plant, from 0.69 to 0.84, and 0.34 to 0.47, respectively, when T_r was incorporated in MLSS concentration-based correlations.

10.3.4.1 SVI link to MLSS concentration, pilot plant

The recorded data points and a fitted trend for pilot plant on-line MLSS concentration and calculated SVI are shown in Figure 10-24. The x₁-axis indicates the MLSS concentration and the y-axis indicates the SVI. The polynomial equation, with the values for the 6 parameters, is indicated on Figure 10-24.

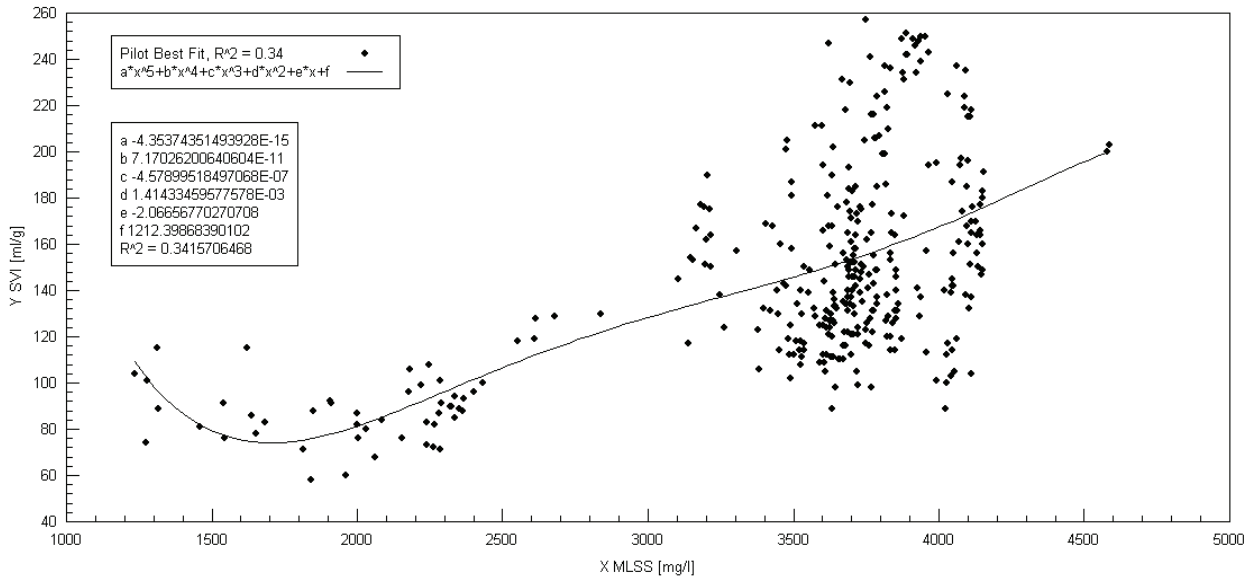


Figure 10-24 SVI related to MLSS, pilot plant, Best-fit, $R^2 = 0.34$

The best-fit curve for SVI related to MLSS concentration is represented by a 6 parameter fifth order 2-dimensional polynomial with a R^2 of 0.34, as shown in Figure 10-24. The direct relationship between SVI as the response variable and MLSS concentration as the dependent variable is confirmed, since the SVI increases as the MLSS concentration increases. The large amount of SVI data scatter in the higher MLSS concentration region is visible on Figure 10-24.

10.3.4.2 SVI link to T_r , pilot plant

The recorded data points and a fitted trend for the pilot plant on-line T_r and calculated SVI are shown in Figure 10-25. The x_1 -axis indicates the T_r and the y-axis indicates the SVI. The tenth order polynomial with the values for the 11 parameters are indicated on Figure 10-25.

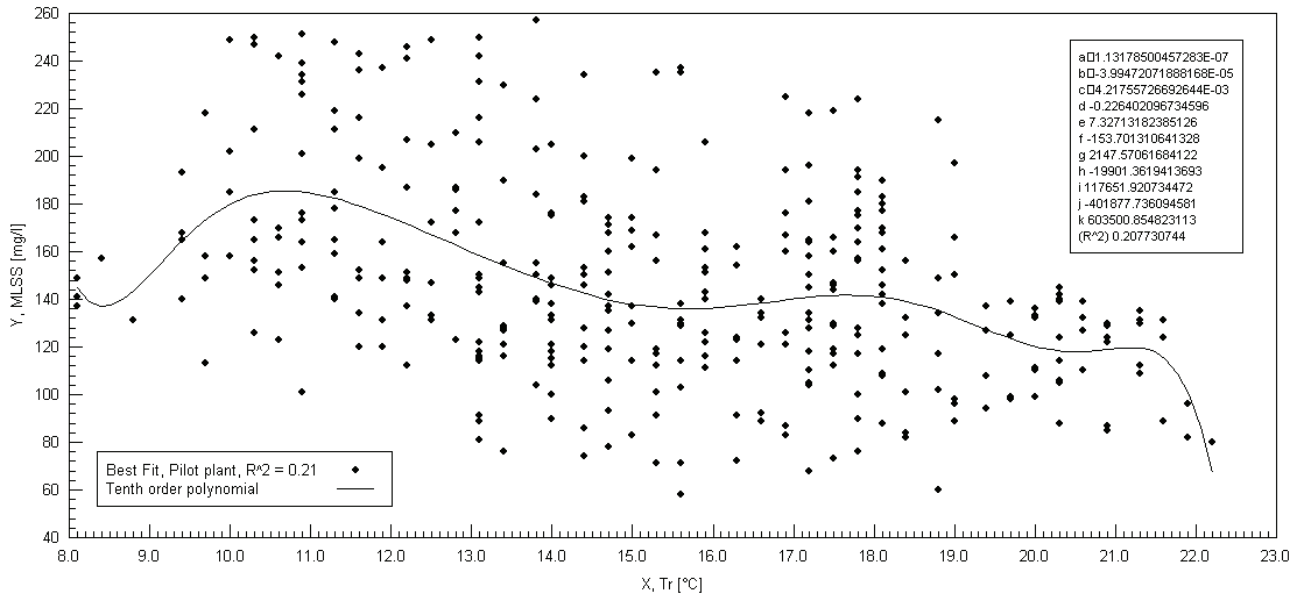


Figure 10-25 SVI related to T_r , pilot plant, Best-fit, $R^2 = 0.21$

The best-fit curve for SVI related to T_r for pilot plant data is represented by an 11 parameter tenth order polynomial 2-dimensional equation, with a R^2 of 0.21. The slight relationship between SVI as the response variable and T_r as the dependent variable is confirmed, since the SVI increases as the T_r increases. The large SVI data scatter around the average trend is visible throughout the fixed T_r ranges.

10.3.4.3 SVI link to MLSS concentration and T_r , pilot plant

The recorded data points and fitted correlation for the pilot on-line MLSS concentration, T_r , and calculated SVI are shown in Figure 10-26. The x_1 -axis indicates the MLSS concentration, the x_2 -axis indicates the T_r , and the y-axis indicates the SVI. The Taylor series polynomial equation, with the values for the 10 parameters, is indicated on Figure 10-26.

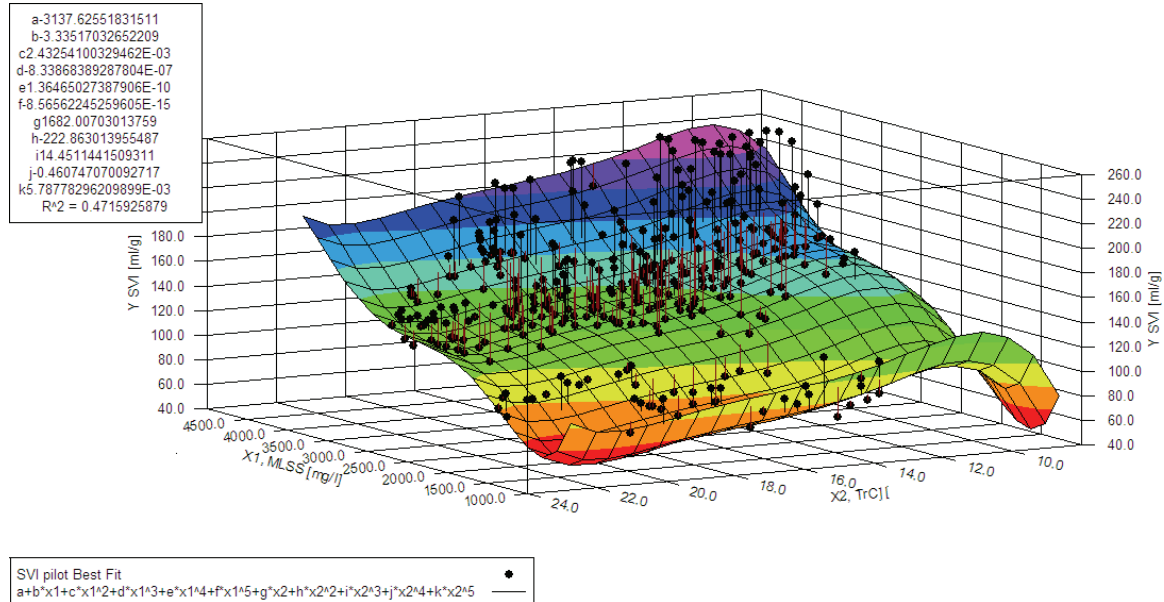


Figure 10-26 SVI related to MLSS and T_r , pilot plant, best-fit, $R^2 = 0.47$

The temperature impact on settling is demonstrated by the improved curve fitting when T_r data is included in the pilot plant SVI evaluation. The best-fit curve for SVI related to MLSS concentration and T_r data is represented by a 10 parameter 3-dimensional equation, with a R^2 of 0.47. Figure 10-26 illustrates the relationship between SVI as the response variable, and MLSS concentration and T_r as the dependent variables. SVI increases as the MLSS concentration increases and the T_r decreases. The inclusion of T_r in SVI correlations improved the curve fitting by a R^2 value of 0.13, from 0.34 to 0.47.

10.3.5 Model fitting: $u_{\max}$ dependence on MLSS concentration and T_r

10.3.5.1 $u_{\max}$ link to MLSS concentration, pilot plant

The recorded data points and a fitted trend for the pilot plant on-line MLSS concentration and calculated $u_{\max}$ are shown in Figure 10-27. The x₁-axis indicates the MLSS concentration and the y-axis indicates the $u_{\max}$. The fifth order inverse logarithm, with the values for the 6 parameters, is indicated on Figure 10-27.

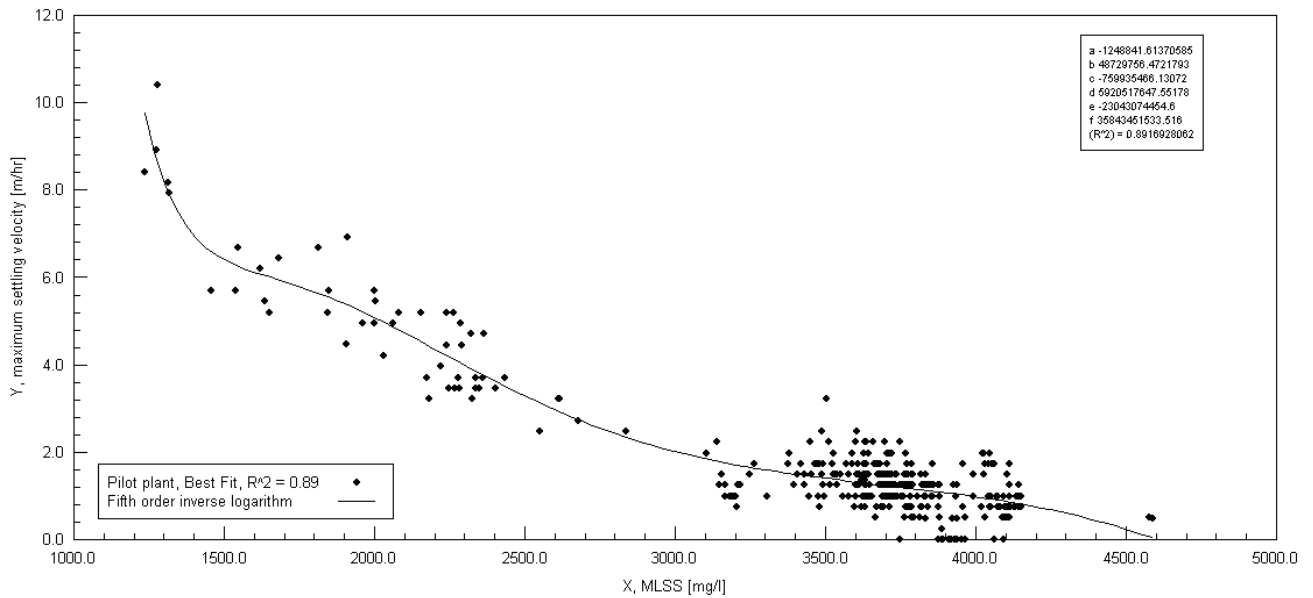


Figure 10-27 $u_{\max}$ related to MLSS, pilot-scale, Best-fit, $R^2 = 0.89$

The best-fit curve for $u_{\max}$ related to MLSS concentration from pilot-scale data is represented by a 6-parameter fifth order inverse logarithm with a R^2 of 0.89, as shown in Figure 10-27. The inverse relationship between $u_{\max}$ as the response variable and MLSS concentration as the dependent variable is confirmed, since the $u_{\max}$ decreases as the MLSS concentration increases. The experimental $u_{\max}$ data scatter is visible throughout the MLSS range, although the high R^2 value indicates less variation than identified with the full-scale plant.

10.3.5.2 $u_{\max}$ link to T_r , pilot plant

The recorded data points and a fitted trend for the full-scale plant on-line T_r and calculated $u_{\max}$ are shown in Figure 10-28. The x_1 -axis indicates the T_r and the y-axis indicates the $u_{\max}$.

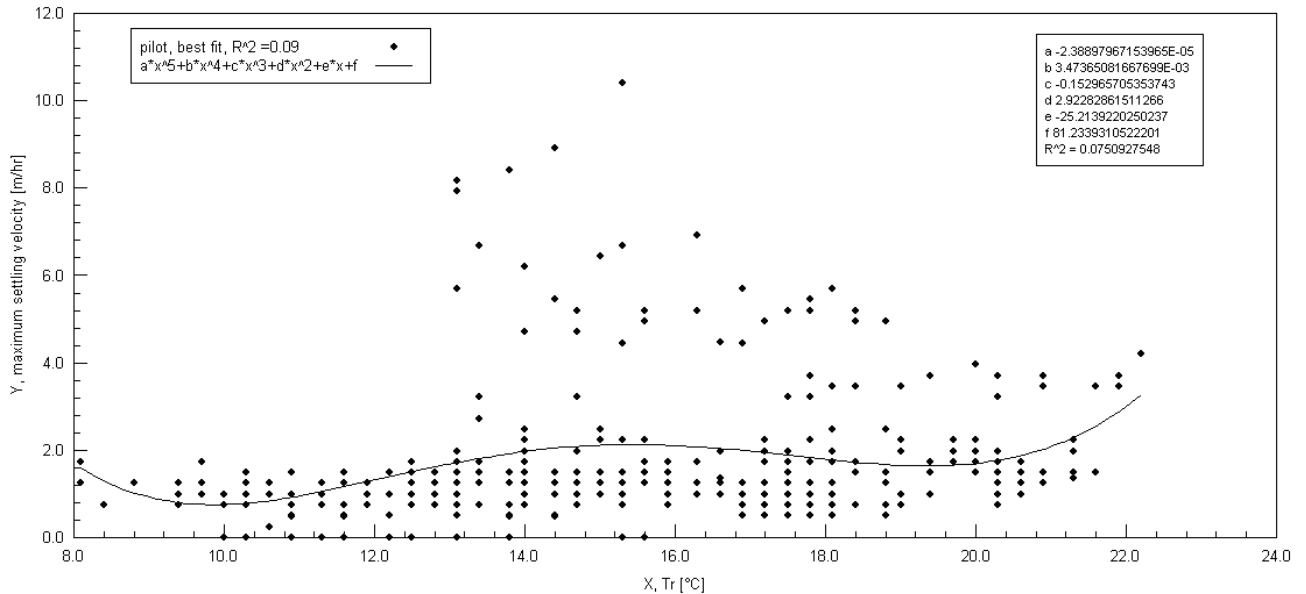


Figure 10-28 $u_{\max}$ related to T_r , pilot plant, $R^2 = 0.09$

The best-fit curve for $u_{\max}$ related to T_r from the pilot data is represented by a 6 parameter 2-dimensional equation with a R^2 of 0.09, as shown in Figure 10-28. There is no definite relationship between $u_{\max}$ as the response variable and T_r as the dependent variable, as the MLSS concentration must be included with the T_r changes.

10.3.5.3 $u_{\max}$ link to MLSS concentration and T_r , pilot plant

The recorded data points and fitted correlation for the pilot plant on-line MLSS concentration, T_r , and calculated $u_{\max}$ are shown in Figure 10-29. The x_1 -axis indicates the MLSS concentration, the x_2 -axis indicates the T_r , and the y-axis indicates the $u_{\max}$.

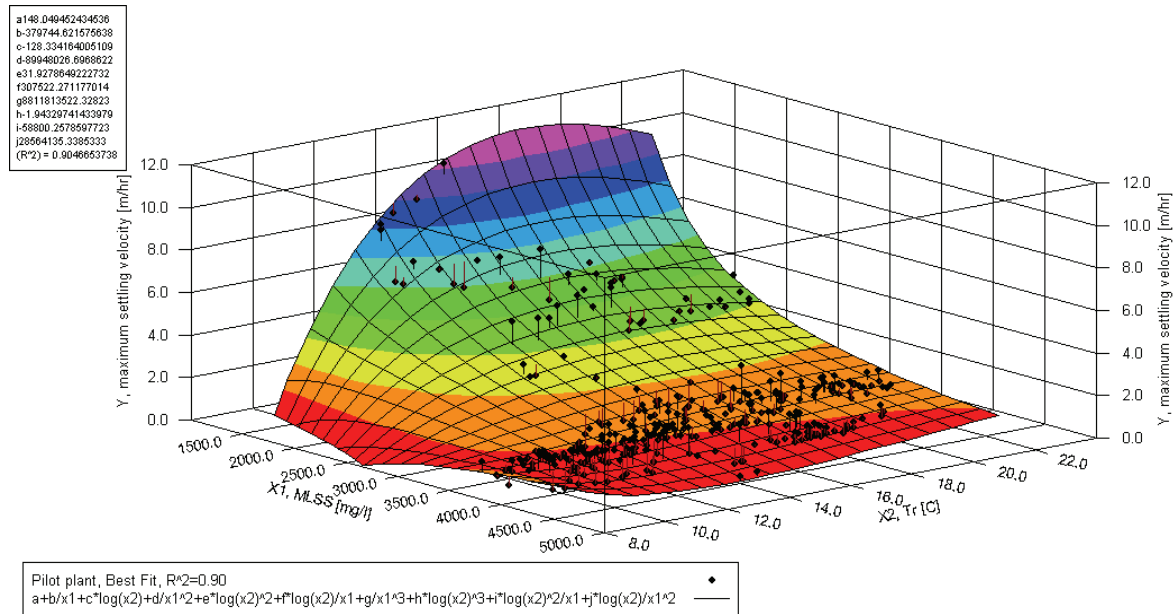


Figure 10-29 $u_{\max}$ related to MLSS and T_r , pilot plant, Best-fit, $R^2 = 0.90$

The temperature impact on settling is not clearly visible by the curve fitting when T_r data is included in the full-scale plant $u_{\max}$ evaluation. The best-fit curve for $u_{\max}$ related to MLSS concentration and T_r data is represented by a 10 parameter 3-dimensional equation with a R^2 of 0.90. Figure 10-29 illustrates the relationship between $u_{\max}$ as the response variable, and MLSS concentration and T_r as the dependent variables. The $u_{\max}$ decreases as the MLSS concentration increases, but $u_{\max}$ increases as the T_r increases. The inclusion of T_r in $u_{\max}$ correlations improved the curve fitting by a negligible R^2 value of 0.01, from 0.89 to 0.90. The $u_{\max}$ calculation based on the 1-minute detection period is too long to provide accurate calculations, with $u_{\max}$ data also too concentrated in the narrow MLSS concentration range. The full-scale plant with less data and diurnal temperature profiles over a smaller MLSS concentration range provides more consistent $u_{\max}$ readings.

10.3.6 Model fitting: t_{umax} dependence on MLSS concentration and T_r

10.3.6.1 t_{umax} link to MLSS concentration, pilot plant

The recorded data points and a fitted trend for the pilot plant on-line MLSS concentration and calculated t_{umax} are shown in Figure 10-30. The x_1 -axis indicates the MLSS concentration and the y-axis indicates the t_{umax} .

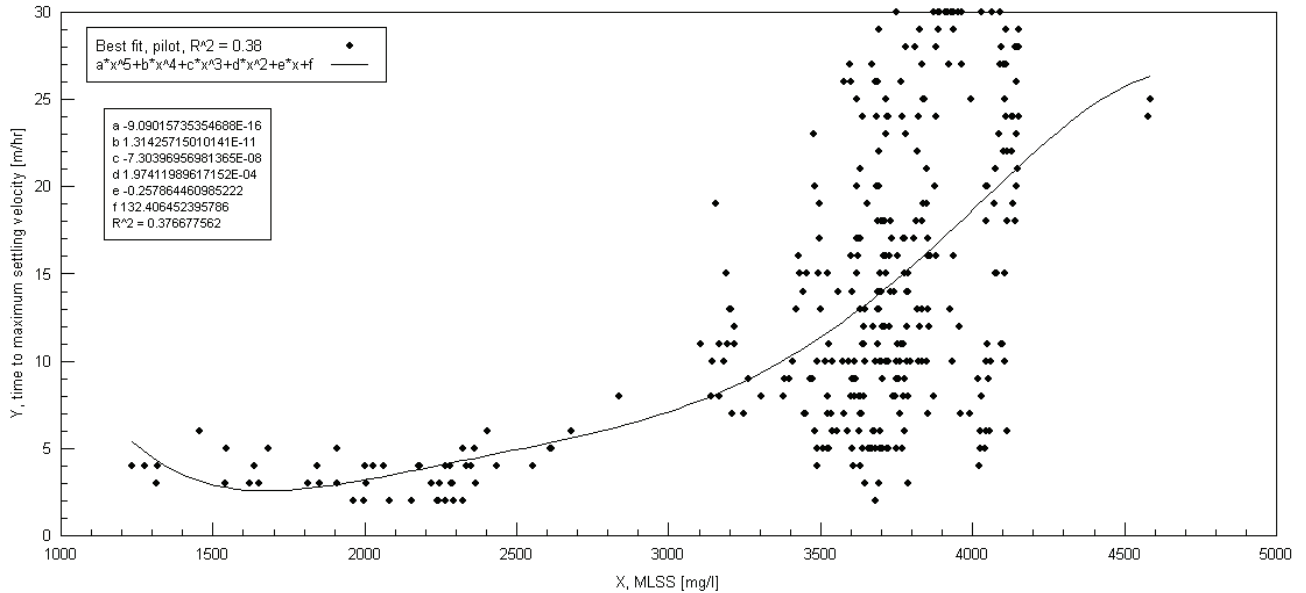


Figure 10-30 t_{umax} related to MLSS, pilot plant, best-fit, $R^2 = 0.38$

The best-fit curve for t_{umax} related to MLSS concentration from pilot plant data is represented by a 6-parameter 2-dimensional polynomial equation with a R^2 of 0.38, as shown in Figure 10-30. The direct relationship between t_{umax} as the response variable and MLSS concentration as the dependent variable is confirmed, since the t_{umax} increases as the MLSS concentration increases. The experimental t_{umax} data scatter is visible throughout the MLSS range.

10.3.6.2 t_{umax} link to T_r , best-fit, pilot plant

The recorded data points and a fitted trend for the full-scale plant on-line T_r and calculated t_{umax} are shown in Figure 10-31. The x_1 -axis indicates the T_r and the y-axis indicates the t_{umax} .

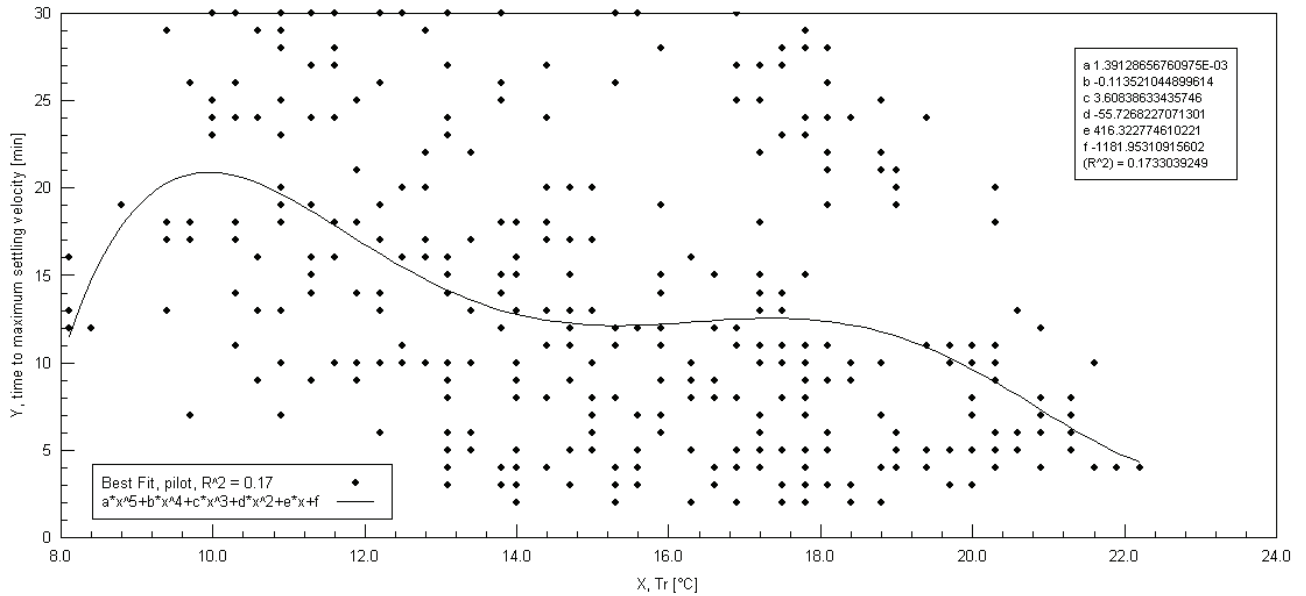


Figure 10-31 t_{umax} related to T_r , pilot-scale, best-fit, $R^2 = 0.17$

The best-fit curve for t_{umax} related to T_r from the pilot plant data is represented by a 6-parameter 2-dimensional polynomial equation with a R^2 of 0.17, as shown in Figure 10-31. There is a slight relationship between t_{umax} as the response variable and T_r as the dependent variable, as the MLSS concentration must be included with the T_r changes. The large experimental t_{umax} data scatter is visible throughout the T_r range, as the MLSS concentration must be considered in the data evaluation.

10.3.6.3 t_{umax} link to MLSS concentration and T_r , pilot plant

The recorded data points and fitted correlation for the pilot plant on-line MLSS concentration, T_r , and calculated t_{umax} are shown in Figure 10-32. The x_1 -axis indicates the MLSS concentration, the x_2 -axis indicates the T_r , and the y-axis indicates the t_{umax} .

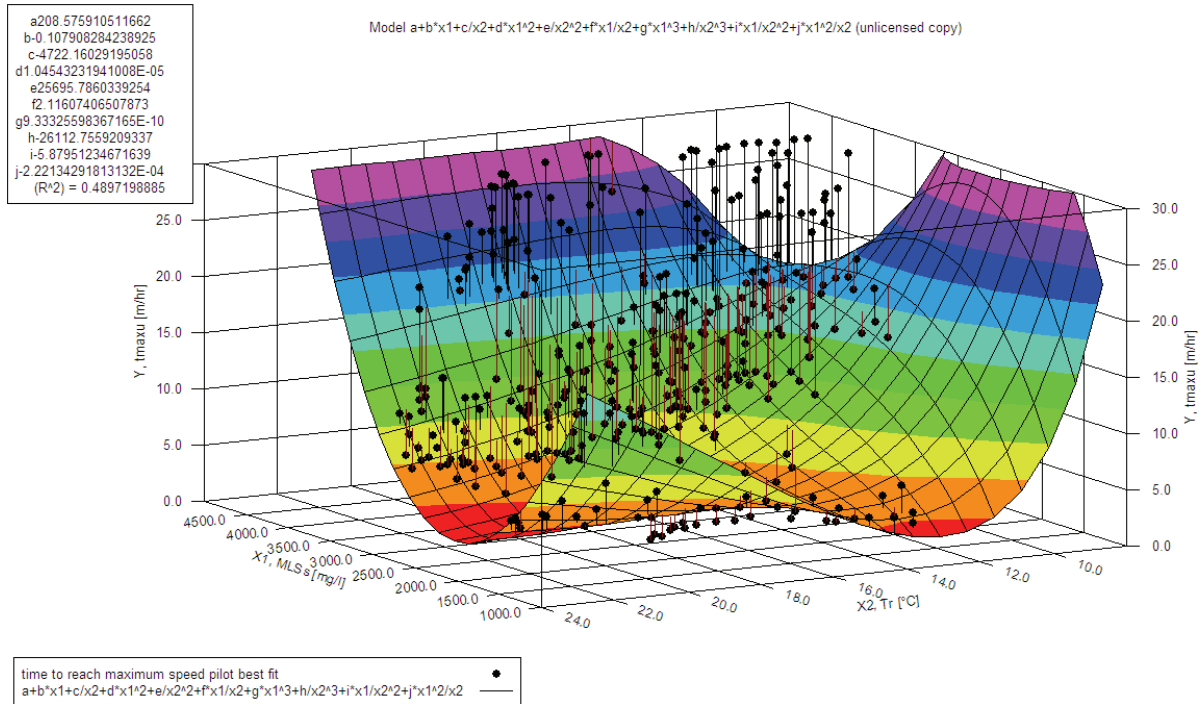


Figure 10-32 t_{umax} related to MLSS and T_r , pilot plant, best-fit, $R^2 = 0.49$

The temperature impact on settling is demonstrated by the improved curve fitting when T_r data is included in the full-scale plant t_{umax} evaluation. The best-fit curve for t_{umax} related to MLSS concentration and T_r data is represented by a 10 parameter 3-dimensional polynomial equation with a R^2 of 0.49, as shown in Figure 10-32. Figure 10-32 illustrates the relationship between t_{umax} as the response variable, and MLSS concentration and T_r as the dependent variables. The t_{umax} increases as the MLSS concentration increases, but t_{umax} decreases as T_r increases. The inclusion of T_r in t_{umax} correlations improved the curve fitting by a factor of 0.11 from 0.38 to 0.49.

10.3.7 Model fitting: Summary of curve-fitting correlations

The inclusion of the reactor temperature improved the sludge settling correlations, as listed in Table 10-8. The average R^2 value for the sludge settling parameters (SVI, time to reach maximum settling velocity, maximum settling velocity) at the full-scale plant was 0.54 without including reactor temperature. The reactor temperature-based correlations improved the average R^2 value by 0.16 to a more acceptable 0.62.

Table 10-8 Summary of MLSS settling correlations incorporating MLSS and T_r

Parameter	Pilot plant		
	MLSS concentration R^2	T_r R^2	MLSS concentration & T_r R^2
SVI [mL/g]	0.34	0.21	0.47
$u_{\max}$ [m/hr]	0.89	0.09	0.90
$t_{\max}$ [min]	0.38	0.17	0.49
Average	0.54	0.16	0.62

A correlation between SVI and the other investigated parameters would be of assistance for design and process optimisation purposes.

10.3.8 SVI correlation procedure

The SVI based settling velocity correlations could be developed experimentally, as illustrated in Figure 10-33 and for the pilot plant. The temperature dependant SVI range could predict the maximum settling velocity and time to reach the maximum settling velocity range for design or process control purposes.

10.3.8.1 SVI and $u_{\max}$ correlation: pilot plant

The recorded data points and a fitted trend for the pilot plant calculated SVI and calculated $u_{\max}$ are shown in Figure 10-33. The x_1 -axis indicates the SVI and the y-axis indicates the $u_{\max}$.

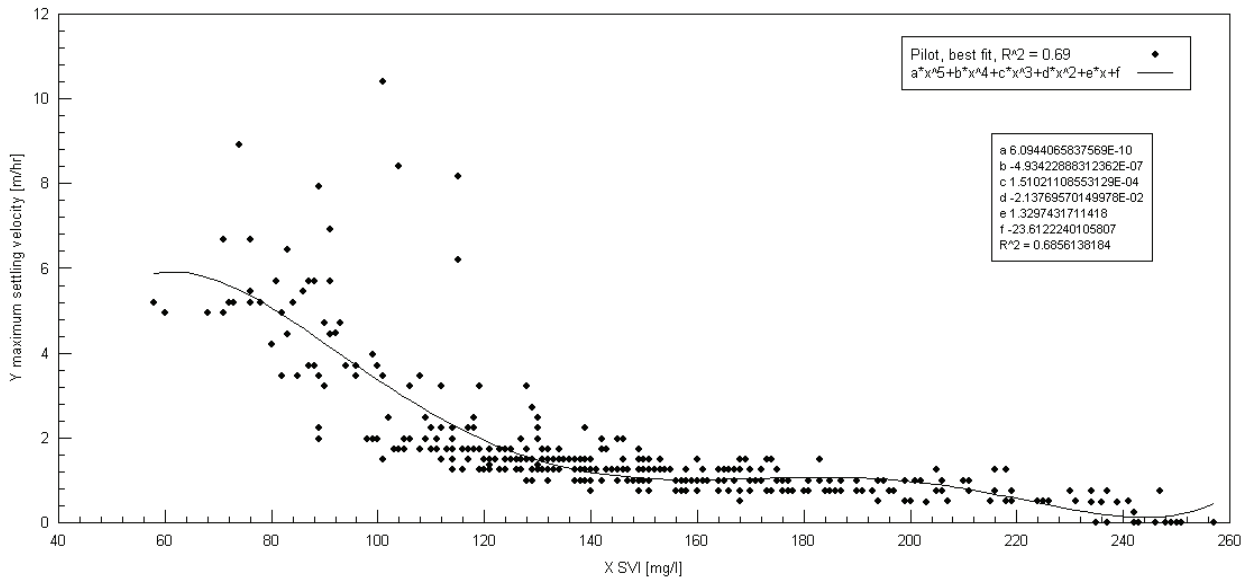


Figure 10-33 $u_{\max}$ related to SVI, pilot, best-fit, $R^2 = 0.69$

The best-fit curve for $u_{\max}$ related to T_r from the pilot plant data is represented by a 6 parameter 2-dimensional polynomial equation with a R^2 of 0.69, as shown in Figure 10-33. The inclusion of reactor temperature in the batch settling tests resulted in a calculated SVI range that correlates in an inverse relationship with $u_{\max}$.

10.3.8.2 SVI and $t_{\max}$ correlation: pilot plant

The best-fit curve for $t_{\max}$ related to T_r from the pilot plant data is represented by a 6 parameter 2-dimensional polynomial equation with a R^2 of 0.74, as shown in Figure 10-35. The inclusion of reactor temperature in the batch settling tests resulted in a calculated SVI range that correlates in a direct relationship with $t_{\max}$.

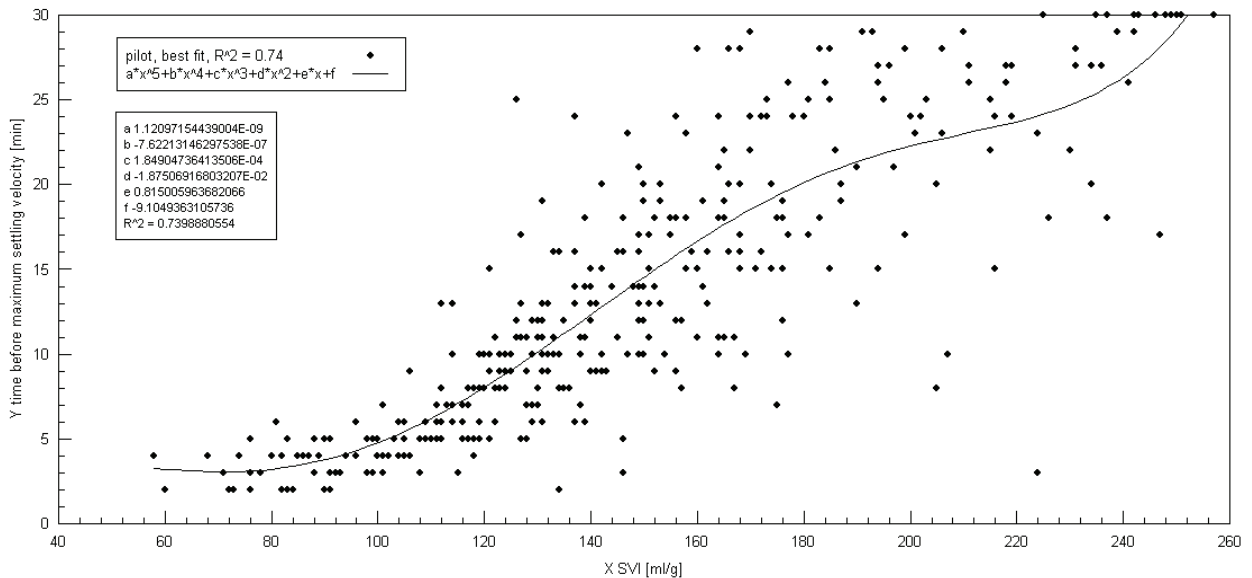


Figure 10-34 $t_{\max}$ related to SVI, pilot, best fit, $R^2 = 0.74$

10.3.9 SVI and $u_{\max}$ and $t_{\max}$: summary of curve-fitting correlations

The SVI data was obtained from on-line automated batch settling tests. These on-line settling tests include the monitoring of reactor temperature variations. The calculated SVI was therefore correlated with temperature-based $u_{\max}$ and $t_{\max}$, as summarised in Table 5-3.

Table 10-9 Summary of SVI correlations with $u_{\max}$ and $t_{\max}$

	Pilot plant SVI R^2
$u_{\max}$	0.69
$t_{\max}$	0.74

The R^2 of 0.9 and 0.95 for the pilot plant illustrate the effect of T_r during MLSS settling. The temperature based SVI R^2 in Table 5-3 provides improved correlations, when compared to the MLSS concentration based correlations summarised in Table 5-2.

Table 10-10 Parameter values for polynomial representing SVI correlations

$y = a * x^5 + b * x^4 + c * x^3 + d * x^2 + e * x + f, x = \text{SVI [ml/g]}$		
	$y = u_{\max}$ [m/hr]	$y = t_{\max}$ [min]
a	6.094E-10	1.121E-9
b	-4.934E-7	-7.622E-7
c	1.510E-4	1.849E-4
d	-2.138E-2	-1.875E-2
e	1.330	0.815
f	-23.61	-9.105
R^2	0.69	0.74

The on-line SVI based correlations with MLSS settling parameters illustrate the benefits of using automatic settling meters that detect the settling profile at the actual T_r . MLSS settling characteristics are plant specific (Wilén, 2006), and SVI based on-line correlations will therefore reflect the responses of individual plant settling parameters over operational MLSS concentration and T_r ranges.

An on-line MLSS settling meter can predict the settling characteristics of an activated sludge plant for design and operational purposes:

- A SVI correlation was developed with on-line reactor MLSS concentration and T_r
- The SVI range could now be predicted from the known or assumed operational MLSS concentration and T_r ranges.
- SVI correlations were developed with calculated $u_{\max}$ and $t_{\max}$
- The $u_{\max}$ and $t_{\max}$ range could now be predicted from the predicted SVI range

10.3.10 Simplified settling models: MLSS concentration and T_r

A simple three-parameter polynomial was chosen as the regression model for 11 settling response variables:

$$y = a + \frac{b}{x_1} + \frac{c}{x_2},$$

with x_1 = MLSS concentration [mg/ℓ], $x_2 = T_r$ [°C], and a, b, c are regression constants.

This basic format is easy to use, as summarised in Table 10-11. The 11 equations are a general representation of the experimental data, and the data is only valid within the experimental MLSS concentration and T_r boundary conditions.

Table 10-11 Summary of regression model constants for settling parameters

Parameter	Pilot-scale plant, n = 354 1235 mg/ℓ < MLSS < 4588 mg/ℓ, ave = 3504, st dev 654 8.1 °C < T_r < 22.2°C, ave =15.4, st dev = 3.3 Model: $a + \frac{b}{MLSS} + \frac{c}{Tr}$				
	a	b	c	R ²	R ² Best-fit
SVI	151.8484	-211430.4978	865.6383	0.37	0.47
t _{umax}	14.3877	-37677.9192	151.5719	0.32	0.49
u _{max}	-2.1734	14785.4383	-8.3009	0.89	0.90
u _{ave}	0.1934	1012.0396	-2.4156	0.54	0.67
h	262.3008	-505175.3270	1204.3701	0.54	0.67
u1	-1.5885	7802.3884	-5.4562	0.84	0.92
u2	0.8020	871.7112	-9.6561	0.19	0.39
u3	0.7910	-687.0584	-2.9732	0.06	0.29
u4	0.4088	-669.9684	1.5308	0.10	0.23
u5	0.3156	-580.6890	1.3003	0.17	0.31
u6	0.2733	-544.3766	1.1798	0.18	0.31

The regression models linking SVI, u_{max}, and t_{umax} to MLSS concentration and T_r , as summarised in Table 5-5, are considered as the most relevant correlations for plant design and operational control. The models for u_{ave}, h, and u1 to u6, also summarised in Table 5-5, are developed and presented in Appendix G. The regression model constants a, b, and c are summarised in Table 5-5. The best-fit R² value for each model is provided to ascertain the fittingness of the simplified model according to the R² value of the model.

10.3.11 SVI link with MLSS concentration and T_r

The response relationship of SVI to MLSS concentration and T_r variations obtained from the pilot plant is presented by the following regression model, with $R^2 = 0.37$:

$$\text{SVI} = 151.8 - \frac{211430.5}{\text{MLSS}} + \frac{865.6}{T_r} \quad [\text{m}\ell/\text{g}] \quad \text{Equation 10-1}$$

The plot of this model, valid within the parameter limit values, is presented in Figure 10-35. The x_1 -axis represents the MLSS concentration range of 1235 to 4588 mg/ℓ , the x_2 axis represents the T_r range from 8.1 to 22.2°C, and the y-axis represents the SVI from 40 $\text{m}\ell/\text{g}$ to 213 $\text{m}\ell/\text{g}$. This relationship is represented by a best-fit ten-parameter equation, with a $R^2 = 0.47$.

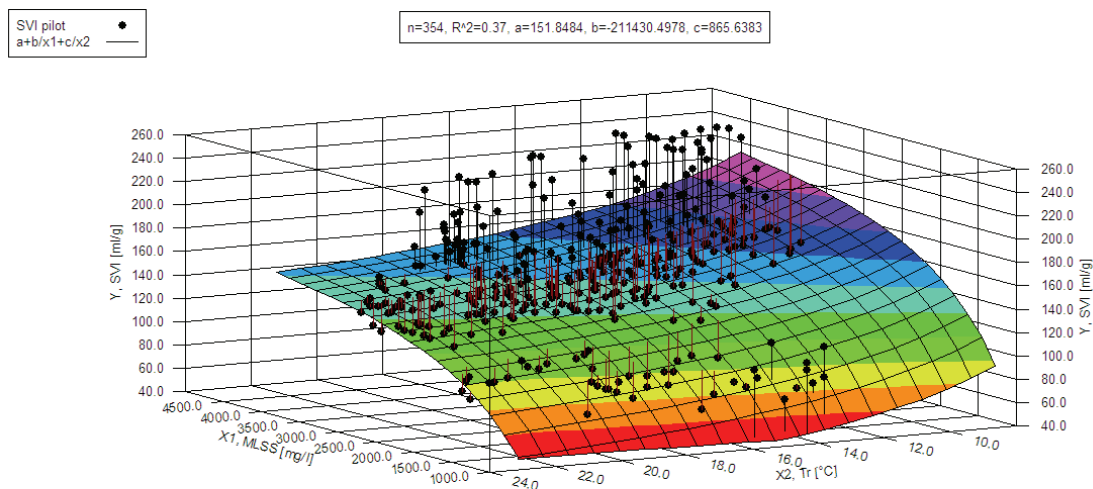


Figure 10-35 SVI dependency on MLSS and T_r , pilot plant

The SVI dependence on the pilot plant T_r can be illustrated by a simulation. At an average constant MLSS concentration of 3000 mg/ℓ , the SVI change due to a T_r reduction from 22.2 to 8.1 °C can be determined according to the SVI-model (Equation 6.2). The SVI increases by 68 $\text{m}\ell/\text{g}$ from 120 to 188 $\text{m}\ell/\text{g}$, with a corresponding relative SVI increase of 5 $\text{m}\ell/\text{g}$ SVI per 1°C T_r reduction.

These two SVI correlations obtained from full-scale and pilot plant MLSS settling tests illustrates batch MLSS settling test result variations. The temperature reduction of 1.8°C at an average 4500 mg/ℓ MLSS concentration contributes to a SVI increase of 21 $\text{m}\ell/\text{g}$. Laboratory sludge samples are taken from the reactor at T_r , usually transported, stored, and tested at a different T_a . The temperature reduction of 14.1°C at an average 3000 mg/ℓ MLSS concentration contributes to a SVI increase of more than 60 $\text{m}\ell/\text{g}$.

10.3.12 $u_{\max}$ link with MLSS concentration and T_r

The response relationship of $u_{\max}$ to MLSS concentration and T_r variations obtained from the pilot plant is presented by the following regression model, with $R^2=0.89$:

$$u_{\max} = -9.3 + \frac{57454.2}{\text{MLSS}} - \frac{39.9}{T_r} \quad [\text{m/hr}] \quad \text{Equation 10-2}$$

The plot of this model, valid within the parameter limit values, is presented in Figure. The x_1 -axis represents the MLSS concentration range of 1235 to 4588 mg/l, the x_2 -axis represents the T_r range from 8.1 to 22.2°C, and the y-axis represents the $u_{\max}$ from 0.7 to 9.4 m/hr. This relationship is represented by a best-fit ten-parameter equation, with a $R^2 = 0.90$.

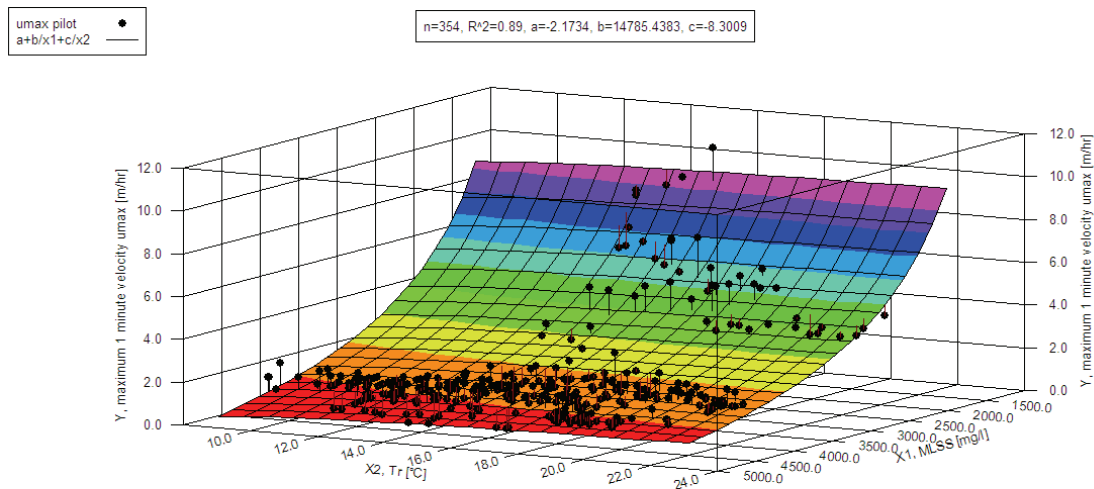


Figure 10-36 Maximum settling velocity dependency on MLSS and temperature, pilot

A simulation can illustrate the $u_{\max}$ dependence on the pilot plant T_r . At an average constant MLSS concentration of 3000 mg/l, the $t_{\max}$ change due to a T_r reduction from 22.2 to 8.1 °C can be determined according to the $t_{\max}$ -models (Equation 6). The $u_{\max}$ decreases by 0.7 m/hr from 2.4 to 1.7 m/hr, with a corresponding relative $u_{\max}$ decrease of 0.05 m/hr per 1°C T_r reduction.

These correlations have important implications for full-scale MLSS settling control. The typical diurnal T_r variation of 1.8°C at a constant MLSS concentration, contributes to a maximum settling velocity change of more than 0.1 m/hr. A more accurate maximum settling velocity must be measured, and it is recommended that the MLSS settling meter recording time interval be changed from 1 to 0.5 minutes. From the relatively low temperature dependence, it might be argued that the 1-minute interval in the MLSS settling meter is not sensitive enough to reflect the true zone settling velocity, and a 30-second period will be recommended for future tests.

The maximum settling velocity correlations have implications for clarifier design. The lower zone settling velocity will require a larger secondary settling tank capacity to ensure the solids load can be accommodated at the higher MLSS concentration and the lower T_r .

10.3.13 $t_{u\max}$ link with MLSS concentration and T_r

The response relationship of $t_{u\max}$ to MLSS concentration and T_r variations obtained from the pilot plant is presented by the following regression model, with $R^2 = 0.32$:

$$t_{u\max} = 14.4 - \frac{376779}{\text{MLSS}} + \frac{151.6}{T_r} \quad [\text{min}] \quad \text{Equation 10-3}$$

The plot of this model, valid within the parameter limit values, is presented in Figure 10-37. The x_1 -axis represents the MLSS concentration range of 1235 to 4588 mg/l, the x_2 - axis represents the T_r range from 8.1 to 22.2°C, and the y-axis represents the $t_{u\max}$ from 0 to 25 minutes. This relationship is represented by a best-fit ten-parameter equation, with a $R^2 = 0.49$.

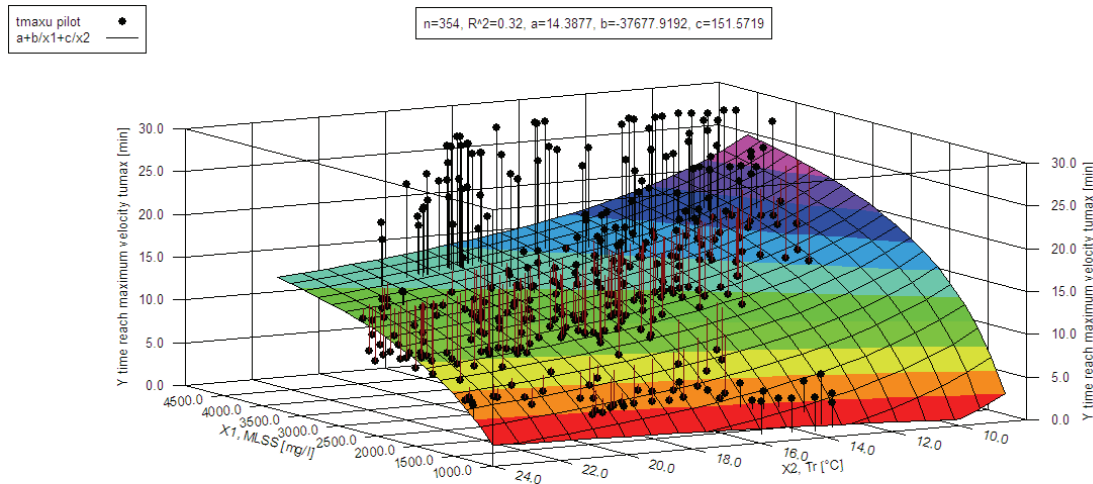


Figure 10-37 Time to $u_{\max}$ dependency on MLSS and T_r , pilot

A simulation can illustrate the $t_{u\max}$ dependence on the pilot plant T_r . At an average constant MLSS concentration of 3000 mg/l, the $t_{u\max}$ change due to a T_r reduction from 22.2 to 8.1 °C can be determined according to the $t_{u\max}$ model (Equation 6.4). The $t_{u\max}$ increases by 11.9 minutes from 8.7 to 20.5 minutes, with a corresponding relative $t_{u\max}$ increase of 0.8 minute per 1°C T_r reduction.

These correlations have implications for full-scale settling control and design. The typical diurnal reactor temperature variation of 1.8°C, at a constant MLSS concentration, contributes to a reflocculation time increasing from 2 to 6 minutes. This relationship is represented by a best-fit equation with a R^2 correlation of 0.83. The reflocculation time delay will require a larger stilling chamber to ensure reflocculation will take place at higher MLSS concentrations and T_r .

The correlations have implications for laboratory sludge sample handling. The dilution of the MLSS concentration of a sample for a DSVI calculation reduces the $t_{u\max}$, as the bioflocs can start settling immediately as discrete particles. Sample handling, transport, storage, and tests at different ambient room temperatures can lead to large temperature variations. The temperature variation of 14.1°C leads to an 11.9 minute variation in time to reach maximum settling velocity. This relationship is represented by a best-fit equation with a $R^2 = 0.49$.

10.3.14 Simplified settling models simulation results summary

An average MLSS concentration of 3000 mg/ℓ was used with the model for the pilot plant. The settling parameters were calculated over the boundary temperature range from 22.2 to 8.1 °C. The results are summarised in Table 10-12. The relative changes to settling parameters indicate a substantial change in all settling parameters, based on a 1°C T_r reduction.

Table 10-12 Settling index and parameters change due to T_r variation, pilot plant

variable	MLSS constant [mg/ℓ]	T_r High [°C]	calculated variable	T_r Low [°C]	T_r Change [°C]	Calculated variable	Variable change	Variable relative Change	unit
SVI	3000	22.2	120	8.1	14.1	188	68	5	ml/g/1°C
t _{umax}	3000	22.2	8.7	8.1	14.1	20.5	11.9	0.8	min/1°C
u _{max}	3000	22.2	2.4	8.1	14.1	1.7	-0.7	-0.05	m/hr/1°C
u _{ave}	3000	22.2	0.4	8.1	14.1	0.2	-0.2	-0.01	m/hr/1°C
h	3000	22.2	148	8.1	14.1	243	94	7	mm/1°C
u ₁	3000	22.2	0.77	8.1	14.1	0.34	-0.43	-0.03	m/hr/1°C
u ₂	3000	22.2	0.66	8.1	14.1	0.00	-0.66	-0.05	m/hr/1°C
u ₃	3000	22.2	0.43	8.1	14.1	0.19	-0.23	-0.02	m/hr/1°C
u ₄	3000	22.2	0.25	8.1	14.1	0.37	0.12	0.01	m/hr/1°C
u ₅	3000	22.2	0.18	8.1	14.1	0.28	0.10	0.01	m/hr/1°C
u ₆	3000	22.2	0.14	8.1	14.1	0.24	0.09	0.01	m/hr/1°C

10.3.15 Summary of results

The on-line MLSS settling evaluation at the pilot plant provides the following results:

- (i) The diurnal profiles follow sinusoidal profiles, with an inverse relationship between T_r and settling meter h, MLSS concentration and SVI
- (ii) The SVI, u_{max}, and t_{umax} were poorly correlated to MLSS concentration alone, with R²-values of 0.34, 0.89, and 0.38. The inclusion of T_r improved the corresponding best-fit correlations to R²-values of 0.47, 0.902, and 0.49.
- (iii) The temperature-based SVI was correlated to u_{max} and t_{umax} at R²-values of 0.69 and 0.47.
- (iv) The basic 3 parameter model provided relative settling parameter changes, based on temperature changes at constant MLSS concentrations:
 - SVI 5 ml/g per 1°C
 - t_{umax} 0.8 minute per 1°C
 - u_{max} -0.05 m/hr per 1°C
 - u_{ave} -0.01 m/hr per 1°C

10.4 Appendix B: T_r measurements: surface and bubble aeration plant data

Table 10-13 Long-term T_r variation data

WCW 1				WCW 2		
Module 1: surface turbine aeration				Module 1: surface turbine aeration		
05 July 2006	Temp @ 08h30	Temp @ 09h45	Temp @ 13h00	26 June 2006	Temp @ 08h00	Temp @ 17:20
Stage 1 North	12.5	12.9	13.4	leg 1 DO1	14.4	15.2
Stage 1 South	12.6	12.9	13.4	leg 2 DO2	14.2	
Stage 2 North	11.5	11.6	12.1	Aerator out	14.1	
Stage 2 South	11.9	11.8	12	RAS return	14.2	
average	12.1	12.3	12.7	Clarifier 1 out	14.2	
				Clarifier 2 out	14.1	
				average leg 12	14.3	15.2
Module 2: submerged diffuser bubble aeration				Module 2: surface turbine aeration		
05 July 2006	Temp @ 08h30	Temp @ 09h45	Temp @ 13h00	26 June 2006	Temp @ 08h00	Temp @ 17:20
North DO 1	17.7	17.8	18	leg 1 DO1	14.2	14.7
South DO 2	17.7	17.8	18	leg 2 DO2	13.8	
North DO 3	17.6	17.7	17.9	Aerator out	13.9	
South DO 4	17.8	18.0	18.3	RAS return	13.9	
North DO 5	17.6	17.7	18	Clarifier 1 out	13.8	
South DO 6	17.7	17.7	17.9	Clarifier 2 out	13.8	
average	17.7	17.8	18.0	average leg 12	14	14.7
Module 3: submerged diffuser bubble aeration				Pilot Plant: submerged diffuser aeration		
05 July 2006	Temp @ 08h30	Temp @ 09h45	Temp @ 13h00	26 June 2006	Temp @ 08:00	Temp @ 17:20
North DO 1	17.5	17.6	17.8	Aerobic 6	9.7	16.6
South DO 2	17.9	18.0	18.2	Ambient	0.3	14.3
North DO 3	17.8	17.8	18			
South DO 4	17.6	17.7	17.9			
North DO 5	17.8	17.9	18.2			
South DO 6	17.6	17.7	17.9			
average	17.7	17.8	18.0			
Module 1: surface turbine aeration				Module 1: surface turbine aeration		
28 October 2006	Temp @ 08h30		Temp @ 12h00	27 October 2006	Temp @ 09h00	Temp @ 13:15
Stage 1 North				leg 1 DO1	21.7	22
Stage 1 South				leg 2 DO2	21.4	21.8
Stage 2 North	20.6		20.5	Aerator out		
Stage 2 South	20.5		20.5	RAS return		
average	20.6		20.5	Clarifier 1 out		
				Clarifier 2 out		
				average leg 12	21.6	21.9
Module 2: submerged diffuser bubble aeration				Module 2: surface turbine aeration		
28 October 2006	Temp @ 08h30		Temp @ 12h00	27 October 2006	Temp @ 09h00	Temp @ 13:15
North DO 1	22.8		23	leg 1 DO1	21.8	22.2
South DO 2	22.6		22.8	leg 2 DO2	21.5	21.9
North DO 3	22.8		23	Aerator out		
South DO 4	23.1		23.4	RAS return		
North DO 5	23.4		23.6	Clarifier 1 out		
South DO 6	23		23.1	Clarifier 2 out		
average	23.0		23.2	average leg 12	21.7	22.1
Module 3: submerged diffuser bubble aeration						
28 October 2006	Temp @ 08h30		Temp @ 12h00			
North DO 1	22.3		22.5			
South DO 2	22.5		22.7			
North DO 3	22.6		22.9			
South DO 4	23		23.3			
North DO 5	22.5		22.8			
South DO 6	22.5		22.7			
average	22.6		22.8			

Remark:

WCW1 = plant 2

WCW2 = plant 1

WCW1a = plant 2 module 1

WCW1b = plant 2 module 2 and 3

WCW2a = plant 1 module 1 and 2

WCW2b = only on-line T_r data

WCW2c = plant 1 pilot

10.5 Appendix C: Raw sewage plant inflow diurnal temperature variation

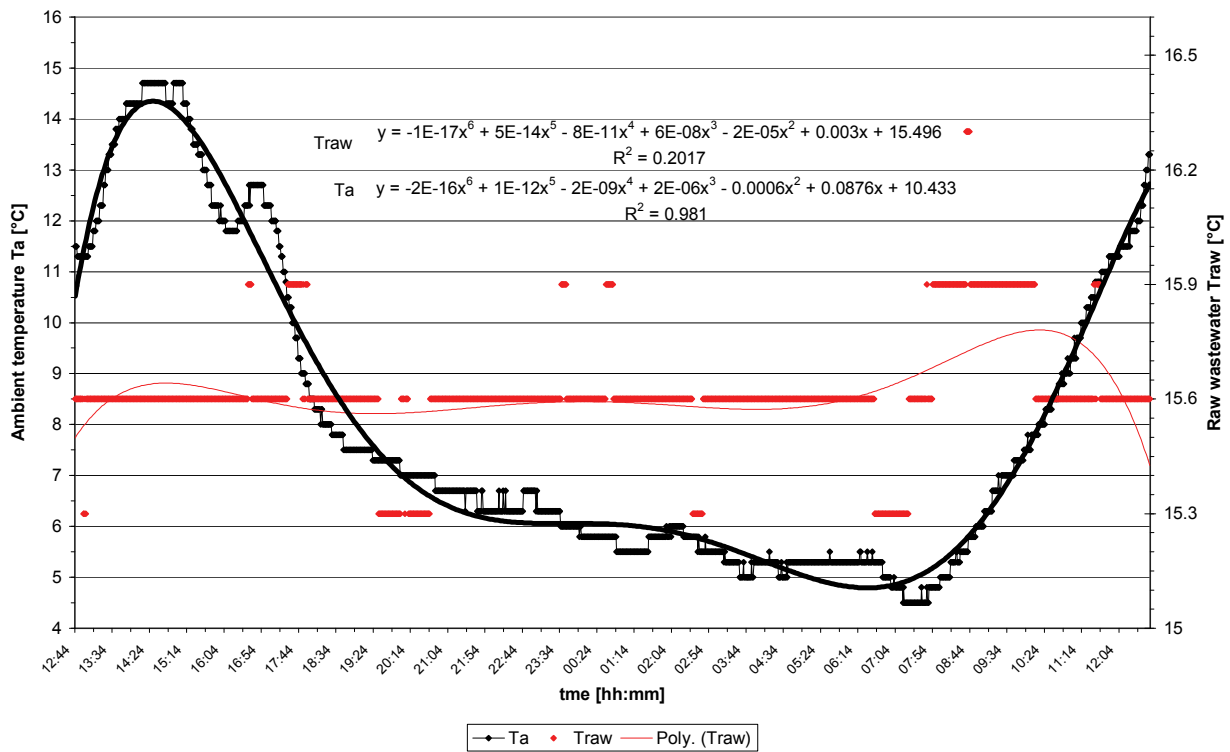


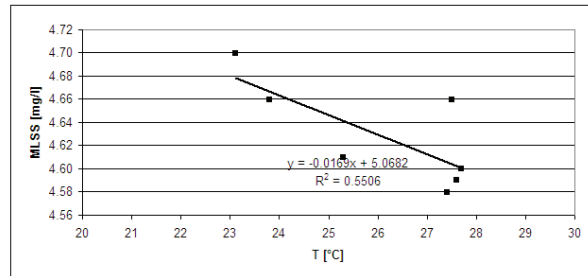
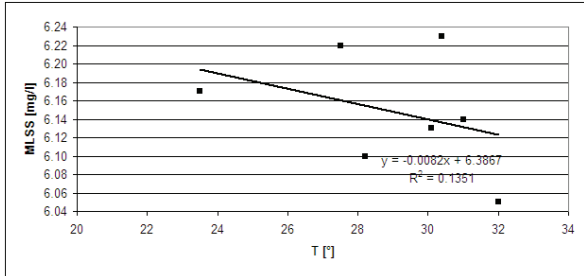
Figure 10-38 Diurnal T_{raw} and T_a profiles

10.6 Appendix D: MLSS concentration meter reading T_s -based variations

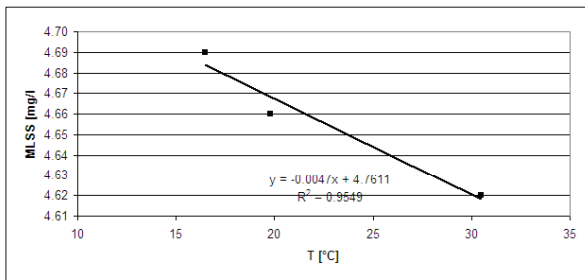
Table 10-14 Test data: MLSS concentration meter reading variation with T_s

exp15-1-7a	time	T	MLSS	T Ambient
	13:53	23.5	6.17	22.1
	14:10	28.2	6.10	
	14:17	30.1	6.13	
	14:20	31.00	6.14	
	14:25	32.00	6.05	
	14:40	30.4	6.23	
	14:54	27.5	6.22	

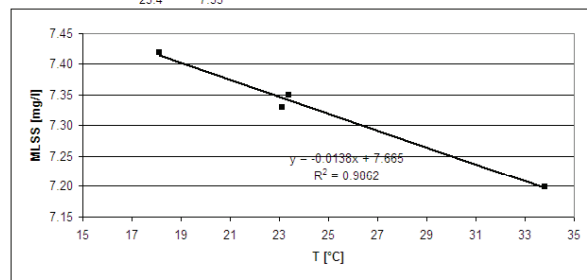
exp15-1-7b	time	T	MLSS
	13:53	23.8	4.66
	14:10	27.5	4.66
	14:17	27.4	4.58
	14:20	27.6	4.59
	14:25	27.7	4.60
	14:40	25.3	4.61
	14:54	23.1	4.70



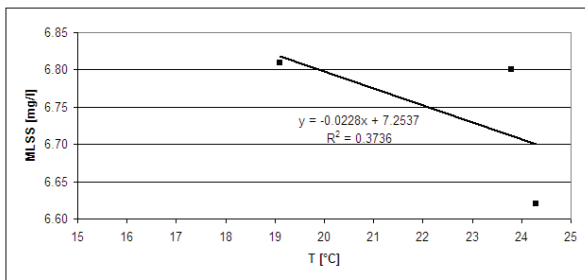
exp4-1-7	time	T	MLSS
	13:53	19.8	4.66
	14:13	30.5	4.62
	14:13	16.5	4.69



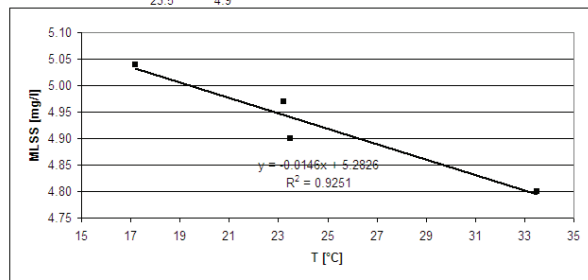
exp8-1-7a	time	T	MLSS
	14:00	23.1	7.33
		18.1	7.42
		33.8	7.20
		23.4	7.35



exp11-1-7	time	T	MLSS	T Ambient
	15:05	23.8	6.80	25.2
		24.3	6.62	
		19.1	6.81	



exp8-1-7b	time	T	MLSS
	14:00	23.2	4.97
		17.2	5.04
		33.5	4.80
		23.5	4.9



	temperature 1	temperature 2	MLSS 1	MLSS 2	change in MLSS
exp15-1-7a	15	25	6.26	6.18	-0.08 g/l
exp15-1-7b	15	25	4.81	4.65	-0.17 g/l
exp4-1-7	15	25	4.69	4.64	-0.05 g/l
exp8-1-7a	15	25	7.46	7.32	-0.14 g/l
exp11-1-7	15	25	6.91	6.68	-0.23 g/l
exp8-1-7b	15	25	5.06	4.92	-0.15 g/l
					-0.14 g/l over 10°C
					-0.014 g/l over 1°C
					-14 mg/l over 1°C

10.7 Appendix E: Batch MLSS settling data

Table 10-15 Summary of experimental batch settling test reactor zone conditions and results

Parameter	Statistics	Anaerobic	Anoxic	Aerobic 1	Aerobic 2	Aerobic 3	Aerobic 4
DO [mg/ℓ]	Average	0.09	0.07	2.34	2.90	1.91	2.94
	St. dev.	0.02	0.01	0.54	0.51	0.48	0.31
	n	29	29	29	29	29	29
T [°C]	Average	17.9	17.9	18.9	18.8	18.1	17.8
	St. dev.	1.2	1.3	1.3	1.2	1.3	1.3
	n	29	29	29	29	29	29
MLSS [mg/ℓ]	Average	3536	3531	3440	3415	3399	3382
	St. dev.	300	263	285	262	258	273
	n	35	35	35	35	35	35
SVI [mℓ/g]	Average	121	123	105	98	104	101
	St. dev.	31	30	12	9	12	11
	n	34	34	34	34	34	34
ISV [m/hr]	Average	2.1	1.9	1.8	2.1	2.0	2.1
	St. dev.	0.6	0.5	0.5	0.6	0.6	0.5
	n	34	34	34	34	34	34
Turb [FNU]	Average	140	98	60	44	31	30
	St. dev.	24	21	15	11	11	9
	n	34	34	34	34	34	34

Table 10-16 Batch MLSS settling sample extended cooling and heating

Temperature change	Position	T [°C] at 0 minutes	T [°C] at 30 minutes	SVI [mℓ/g]	SVI increase [mℓ/g/1°C]	ISV [m/hr]	ISV decrease [m/hr/1°C]	Turbidity [FNU]	Turbidity increase [FNU/1°C]
Cooled	Sun	8.6	16.1	131	-	0.53	-	15	-
Cooled	Shade	6.4	10.8	164	-6.2	0.04	0.09	7	1.5
Heated	Sun	29.0	27.3	106	-	1.76	-	33	-
Heated	Shade	25.5	25.3	106	0	1.76	0	21	6.0

Table 10-17 Batch settling test results data, with temperature and container size variation

Container	Condition & Temperature	SVI 19/6	SVI 21/6	SVI 19/7	SVI Ave	u 19/6	u 21/6	u 19/7	u Ave	Tur 19/6	Tur 21/6	Tur 19/7	Tur Ave
	MLSS [mg/l]	4210	3930	4470	4203	4210	3930	4470	4203	4210	3930	4470	4203
1ℓ	Shade	181	170	172	174	0.00	0.09	0.04	0.04	14	19	9	14
	T 30 [°C]	17.0	19.5	20.9	19.1	17.0	19.5	20.9	19.1	17.0	19.5	20.9	19.1
1ℓ	Sun	105	104	116	108	0.92	1.06	0.11	0.70	20	23	14	19
	T 30 [°C]	21.5	23.8	25.2	23.5	21.5	23.8	25.2	23.5	21.5	23.8	25.2	23.5
2ℓ	Shade	195	137	181	171	0.31	0.88	0.13	0.44	14	-	14	14
	T 30 [°C]	17.0	19.5	20.7	19.1	17.0	19.5	20.7	19.1	17.0	-	20.7	19.1
2ℓ	Cool, shade	-	164	-	164	-	0.04	-	0.04	-	7	-	7
	T 30 [°C]	-	10.8	-	10.8	-	10.8	-	10.8	-	10.8	-	10.8
2ℓ	Cool, sun	-	131	-	131	-	0.53	-	0.53	-	15	-	15
	T 30 [°C]	-	16.1	-	16.1	-	16.1	-	16.1	-	16.1	-	16.1
2ℓ	Heat, shade	-	106	-	106	-	1.76	-	1.76	-	21	-	21
	T 30 [°C]	-	25.3	-	25.3	-	25.3	-	25.3	-	25.3	-	25.3
2ℓ	Heat, sun	-	106	-	106	-	1.76	-	0.76	-	33	-	33
	T 30 [°C]	-	27.3	-	27.3	-	27.3	-	27.3	-	27.3	-	27.3
2ℓ	Dilute, shade	-	122	-	122	-	1.89	-	1.89	-	21	-	21
	T 30 [°C]	-	19.1	-	19.1	-	19.1	-	19.1	-	19.1	-	19.1
2ℓ	Dilute, sun	-	102	-	102	-	2.73	-	2.73	-	23	-	23
	T 30 [°C]	-	23.2	-	23.2	-	23.2	-	23.2	-	23.2	-	23.2
2ℓ	Sun	109	106	119	111	0.62	1.50	0.40	0.84	15	21	23	21
	T 30 [°C]	20.9	23.6	25.1	23.2	20.9	23.6	25.1	23.2	20.9	23.6	25.1	23.2
20ℓ	Sun	112	-	139	126	0.97	-	0.31	0.64	18	-	11	15
	T 30 [°C]	19.0	-	22.2	20.6	19.0	-	22.2	20.6	19.0	-	22.2	20.6

10.7.1 SVI variation

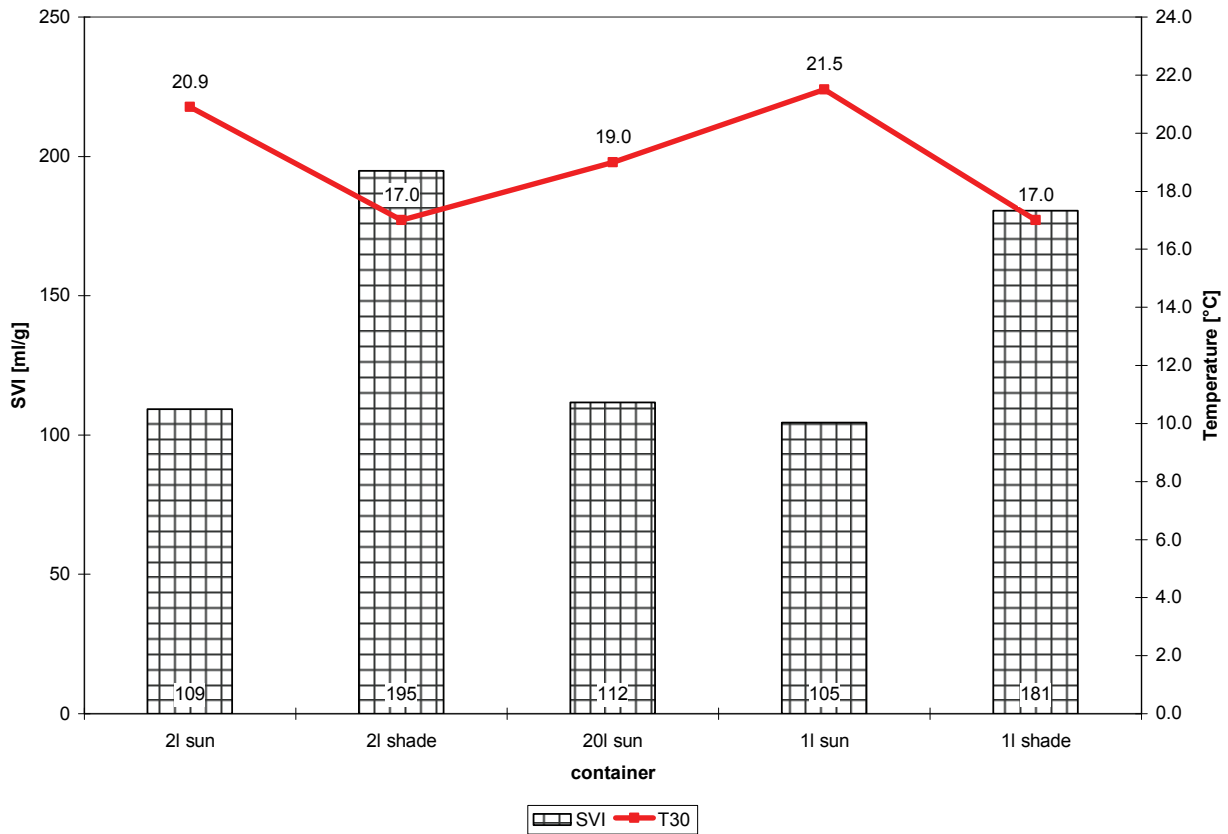


Figure 10-39 SVI, different containers, T_s after 30 min., MLSS 4210 mg/ℓ

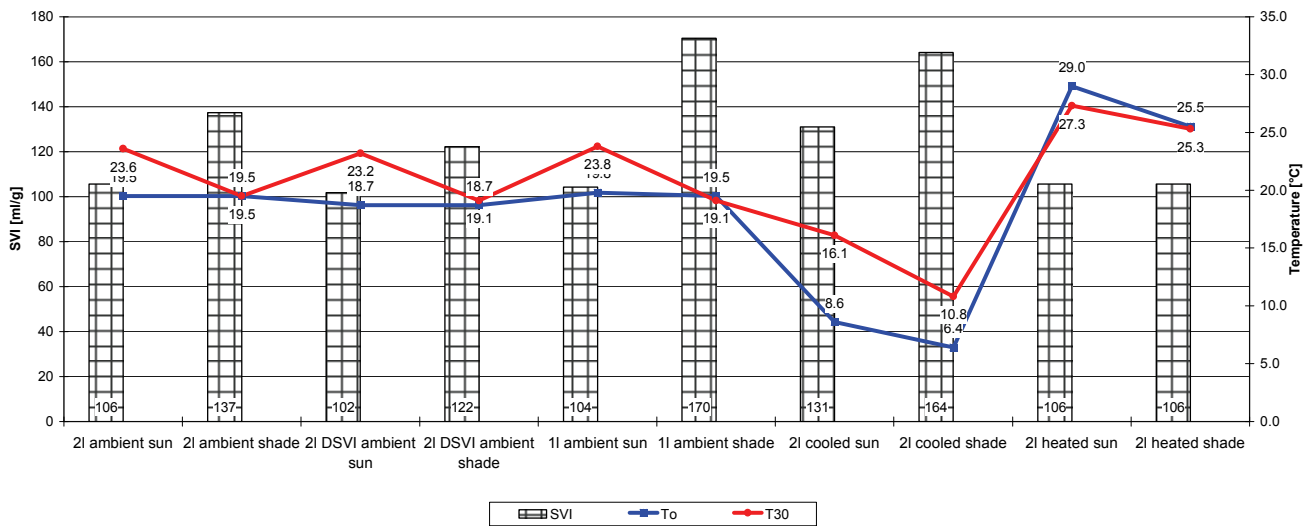


Figure 10-40 SVI, different containers, T_s after 0 and 30 min., MLSS 3930 mg/ℓ

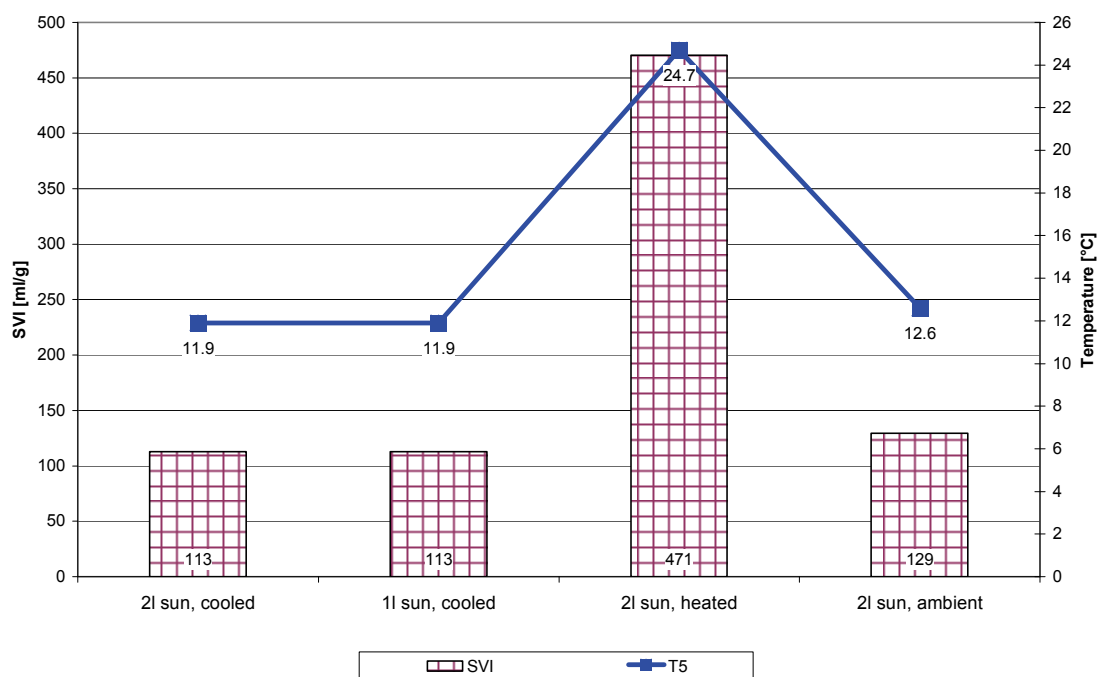


Figure 10-41 SVI, different containers, T_s after 5 min., MLSS 4250 mg/l

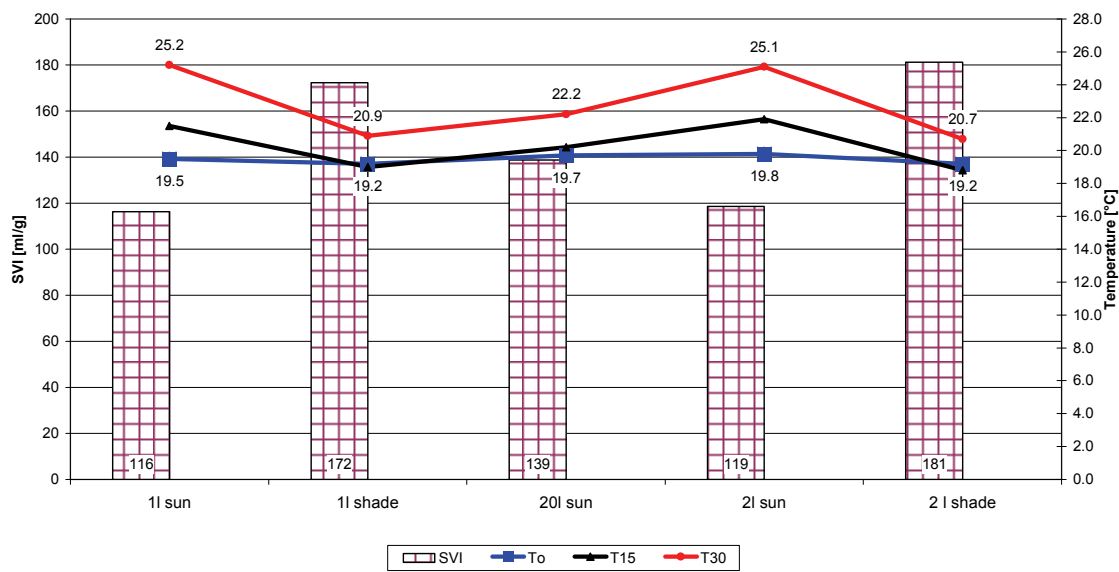


Figure 10-42 SVI, different containers, T_s after 0, 15 and 30 min., MLSS 4470 mg/l

10.7.2 Zone settling velocity variation

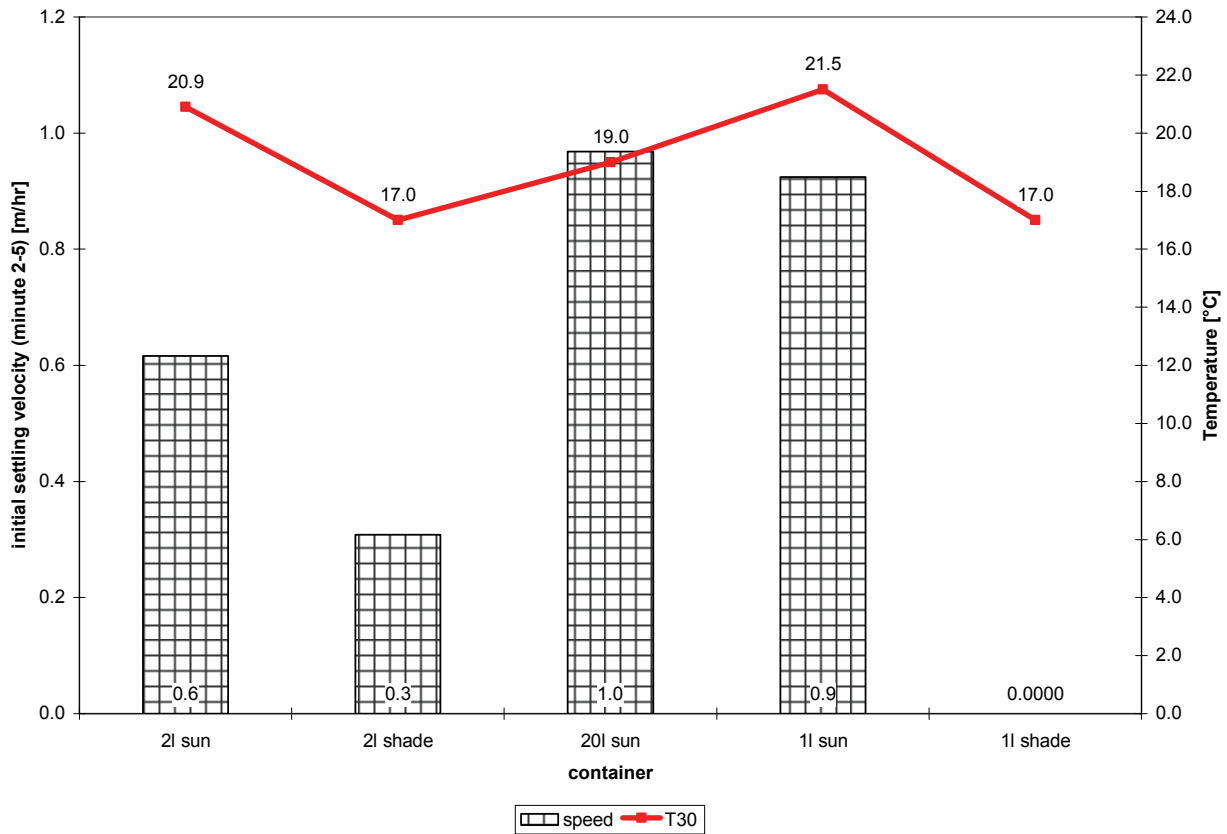


Figure 10-43 Initial settling velocity, T_s after 30 min., MLSS 4210 mg/ℓ

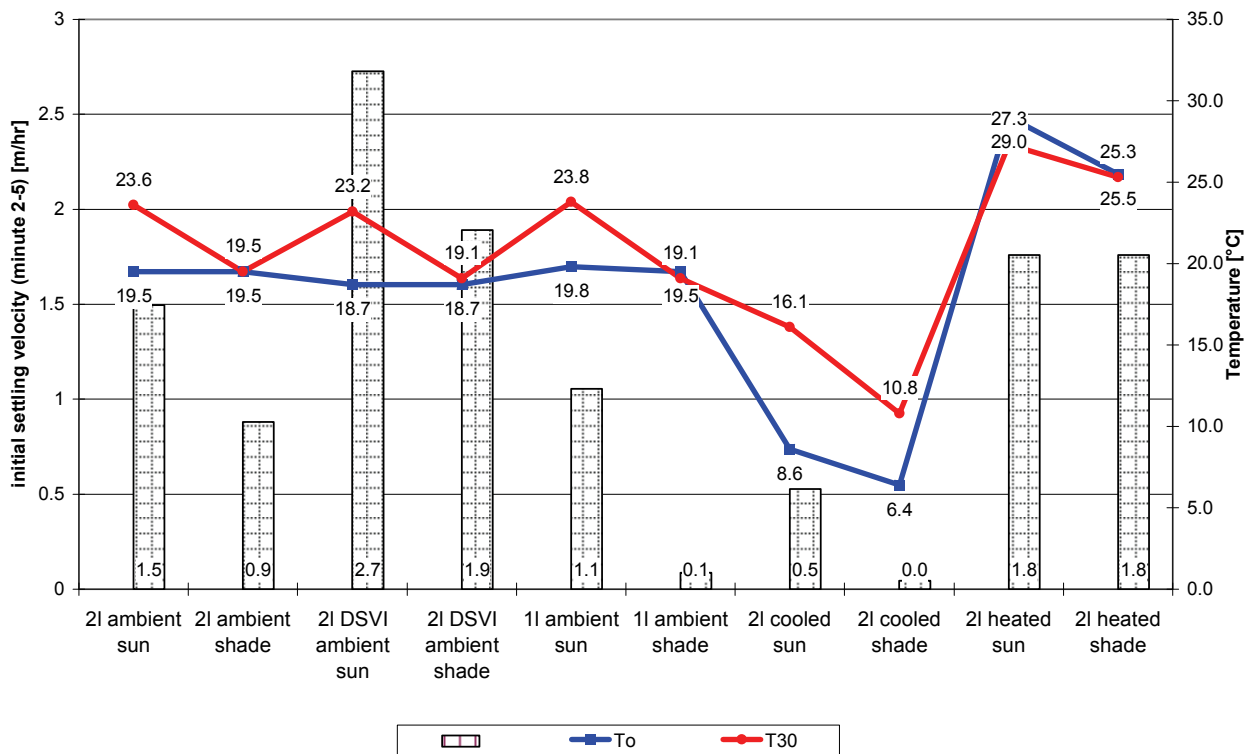


Figure 10-44 ISV, T_s after 0 and 30 min., MLSS 3930 mg/ℓ

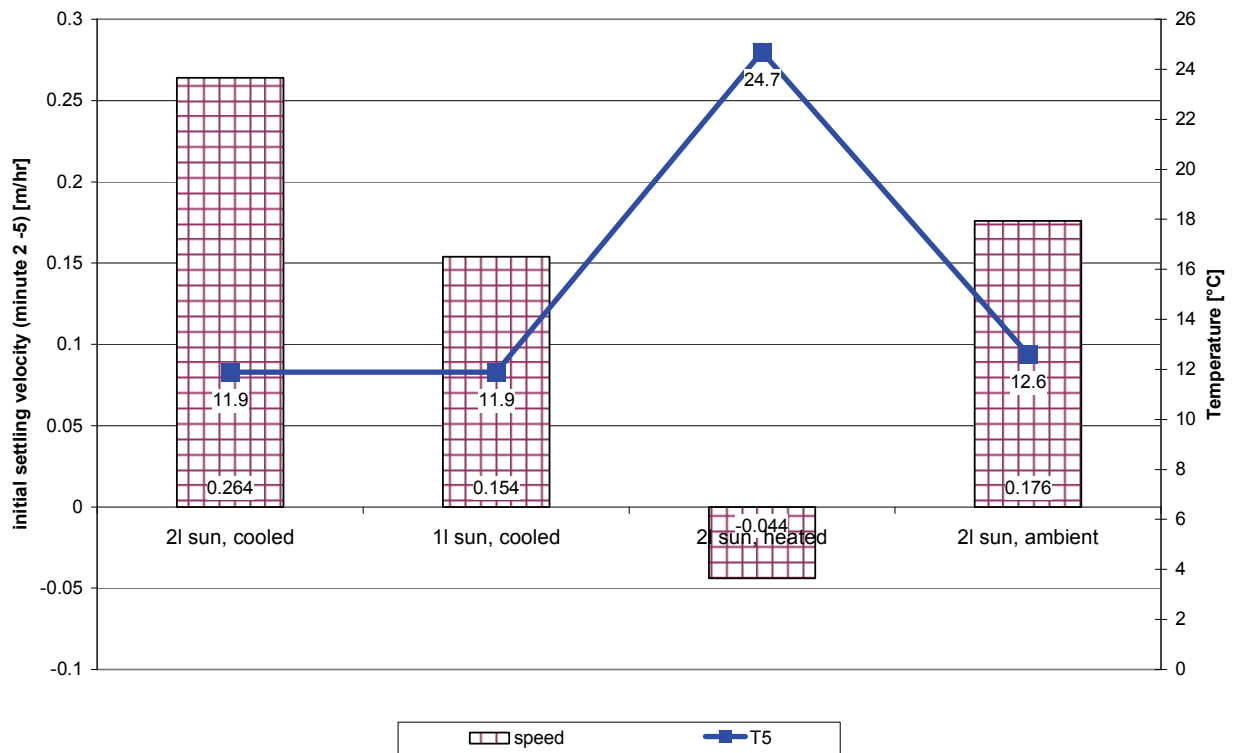


Figure 10-45 ISV, T_s after 5 min., MLSS 4250 mg/l

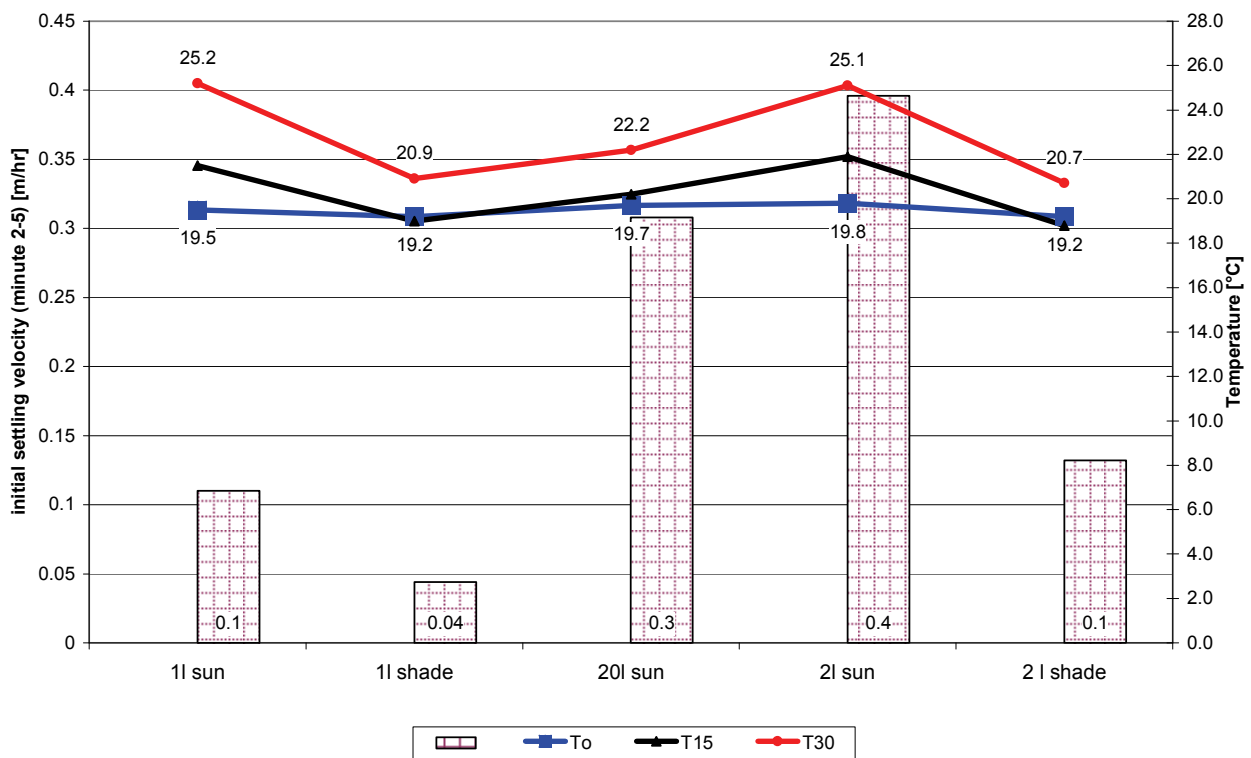


Figure 10-46 ISV, T_s after 0, 15 and 30 min., MLSS 4470 mg/l

10.7.3 Turbidity variation

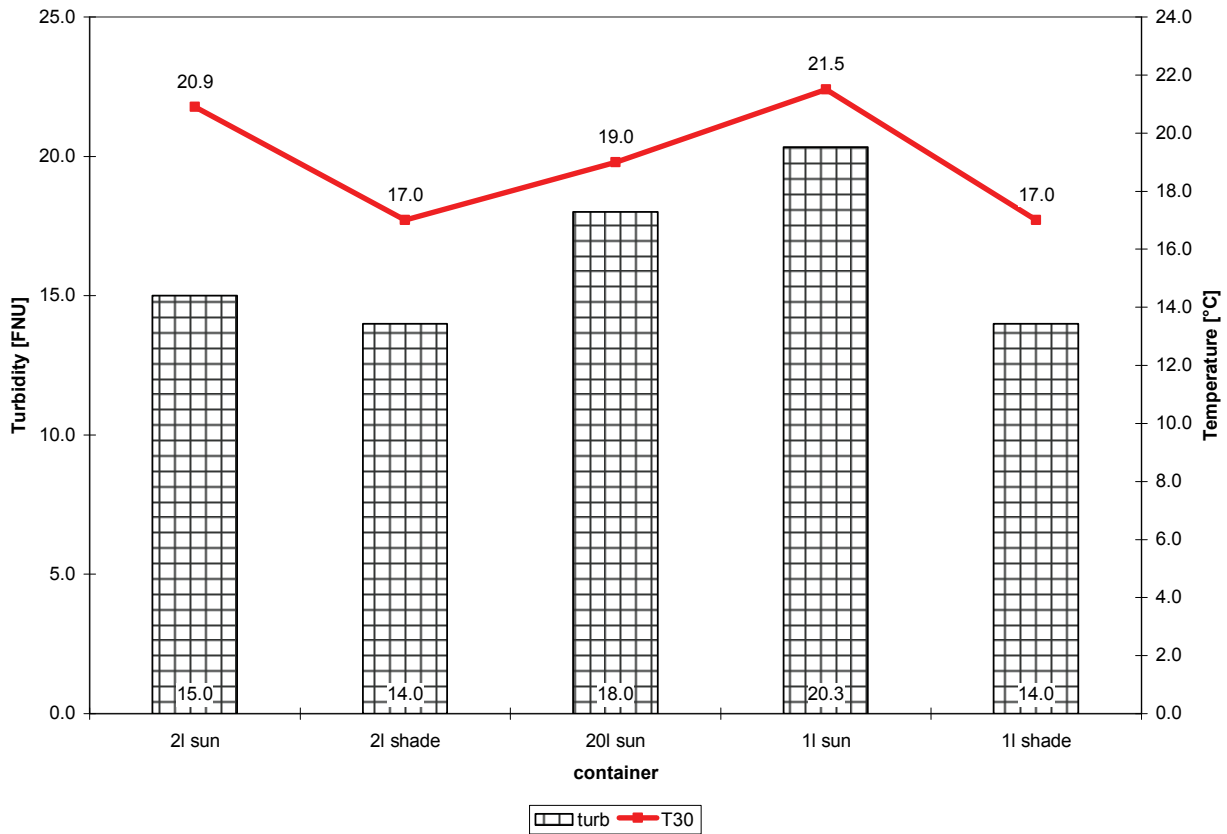


Figure 10-47 Turbidity, 30 min. settling, T_s after 30 min., MLSS 4210 mg/l

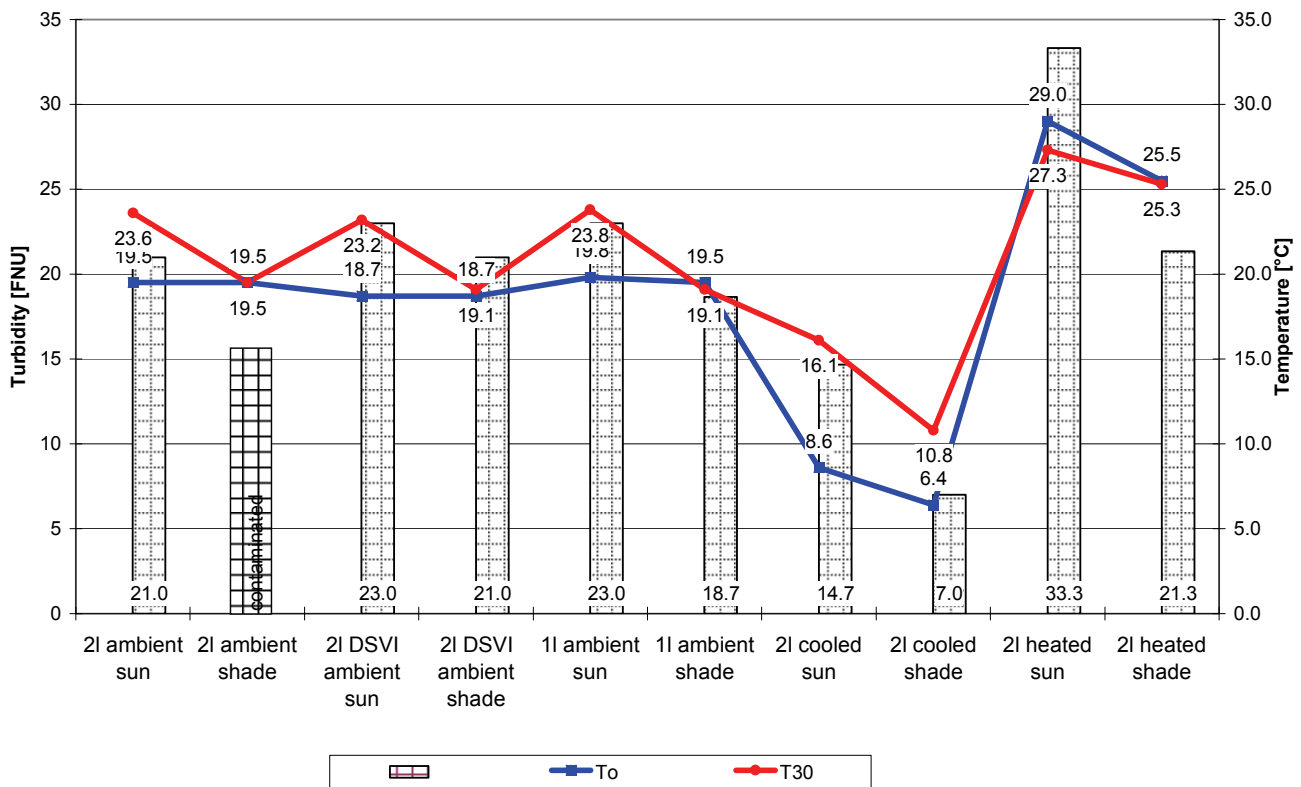


Figure 10-48 Turbidity, 30 min. settling, T_s after 0 and 30 min, MLSS 3930 mg/l

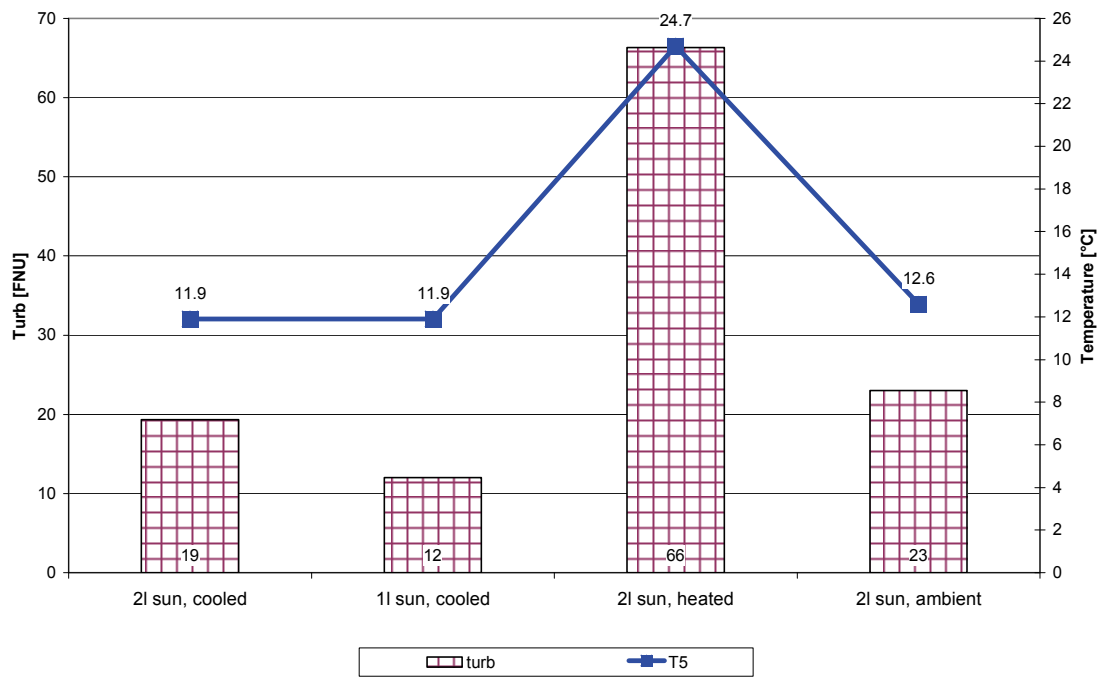


Figure 10-49 Turbidity, 30 min. settling, T_s after 5 min., MLSS 4250 mg/ℓ

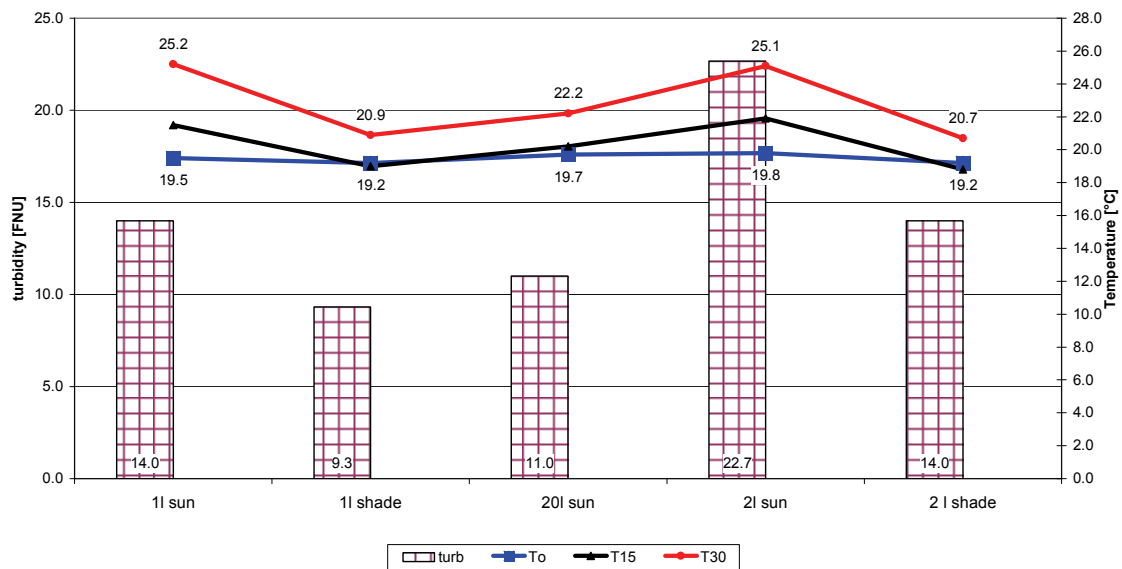


Figure 10-50 Turbidity, 30 min. settling, T_s after 0, 15 and 30 min., MLSS 4470 mg/ℓ

10.8 Appendix F: On-line data

An example of a typical Excel spreadsheet diagram with a 12-hour profile of h and T_a is provided in Figure 10-51. The T_a profile varies from about 5 to 25°C, whereas the 30-minute MLSS settling profiles final h value varies from about 359 mm to 210 mm.

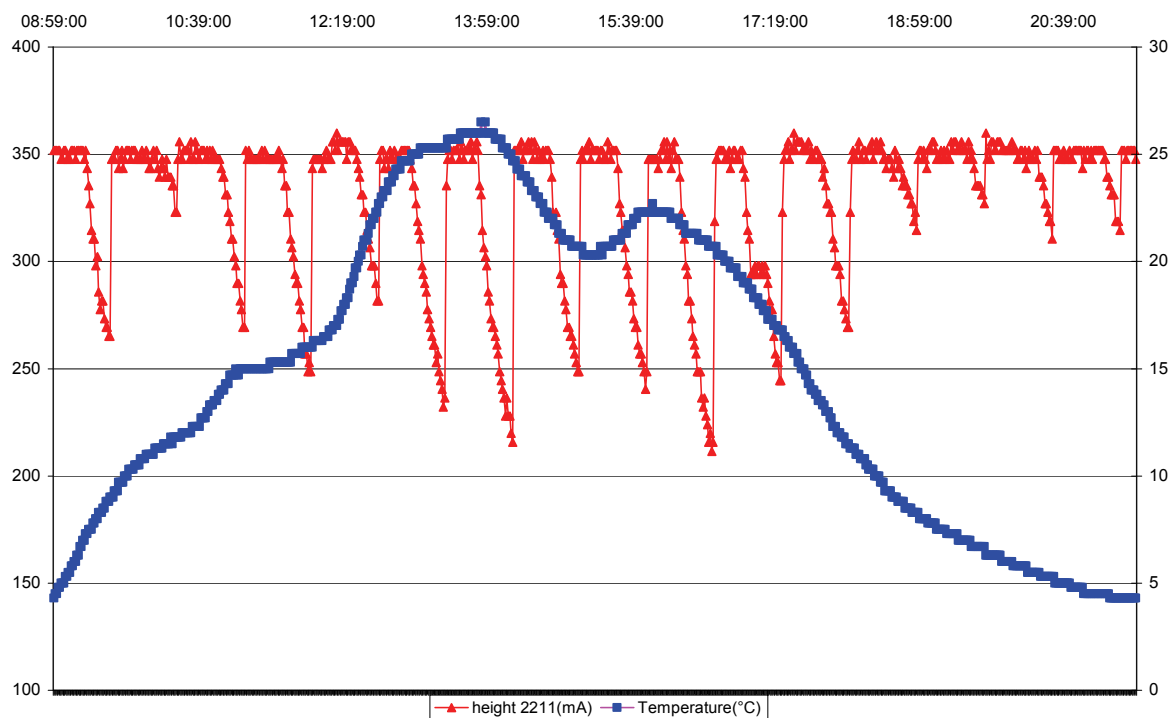
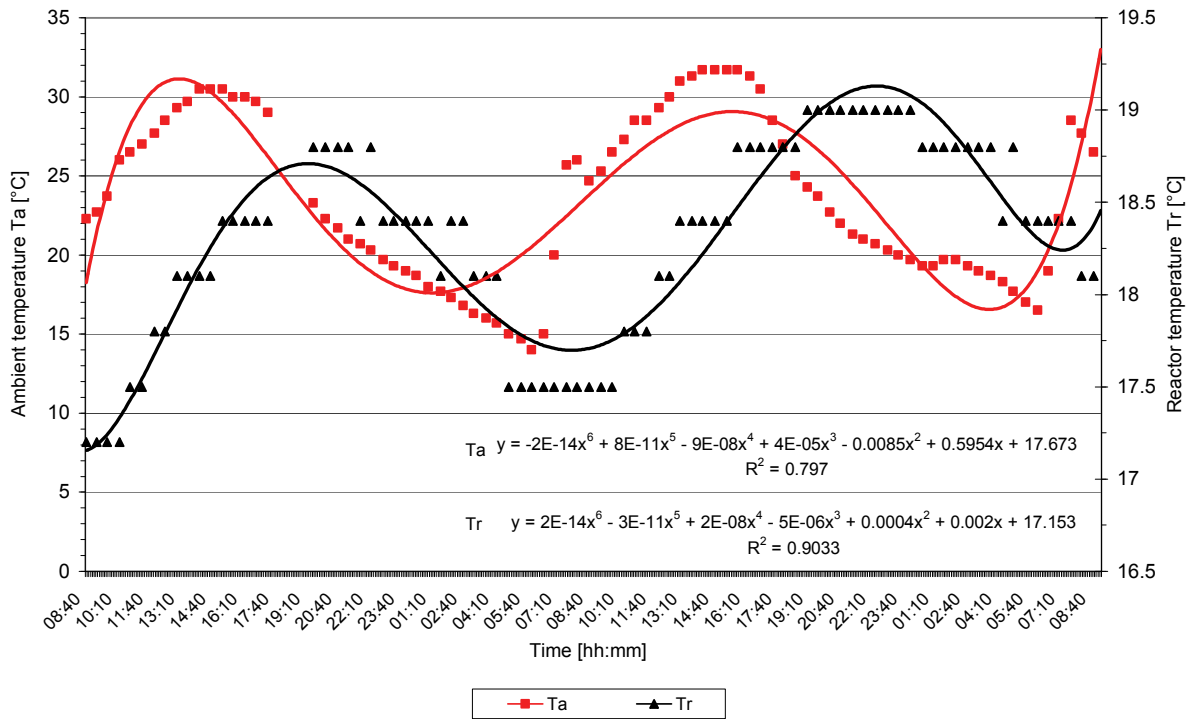
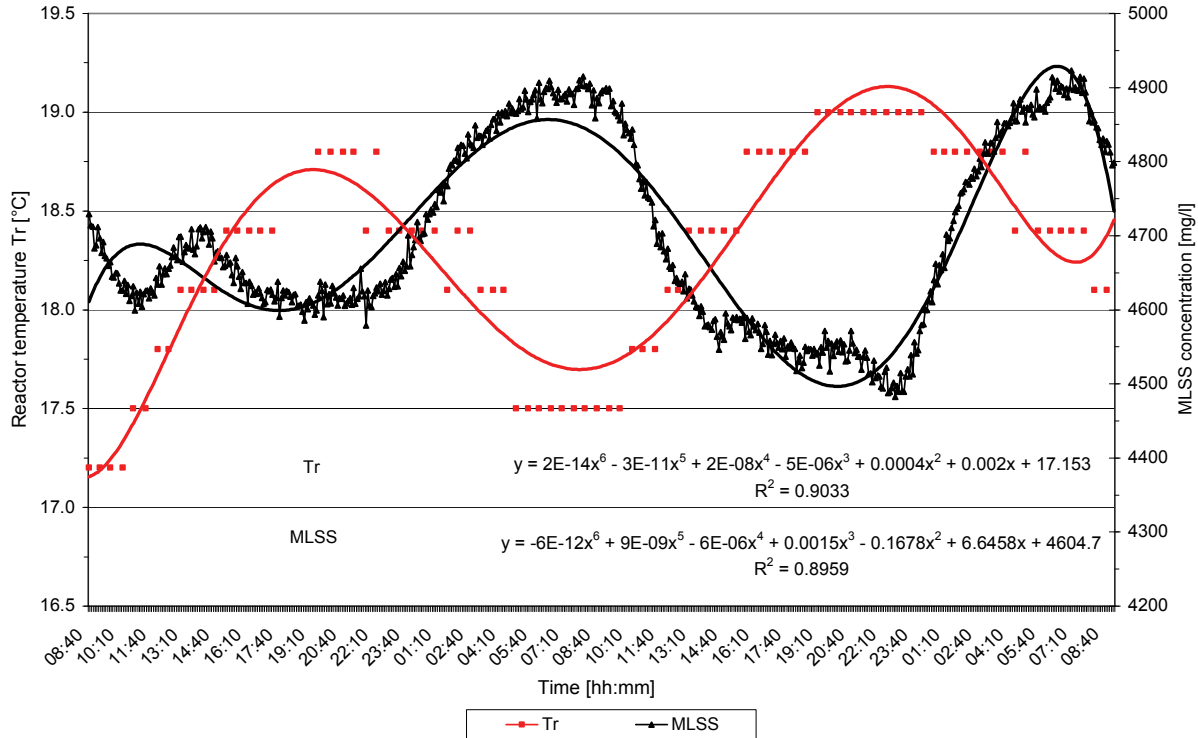


Figure 10-51 Settling profile from MLSS settling meter h and T_a readings over 12 hours

Table 10-18 Summary of on-line experimental data

[illegible]

Figure 10-52 Two-day T_a and T_r profilesFigure 10-53 Two-day T_r and MLSS concentration profiles

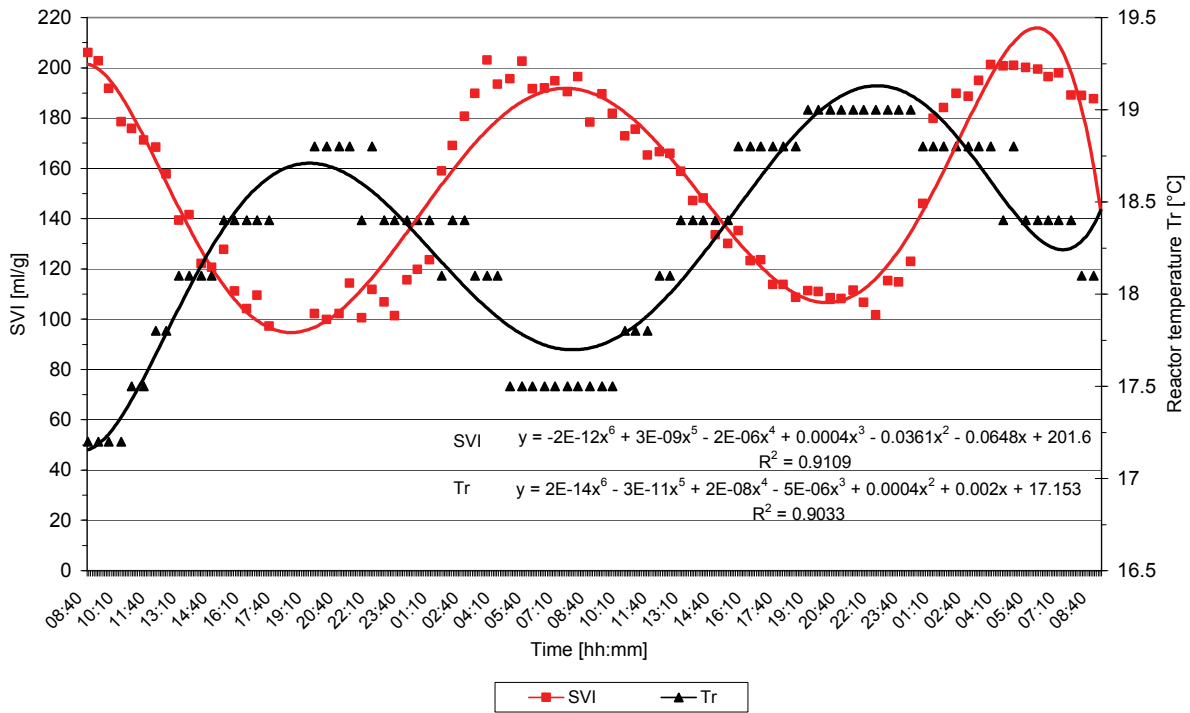
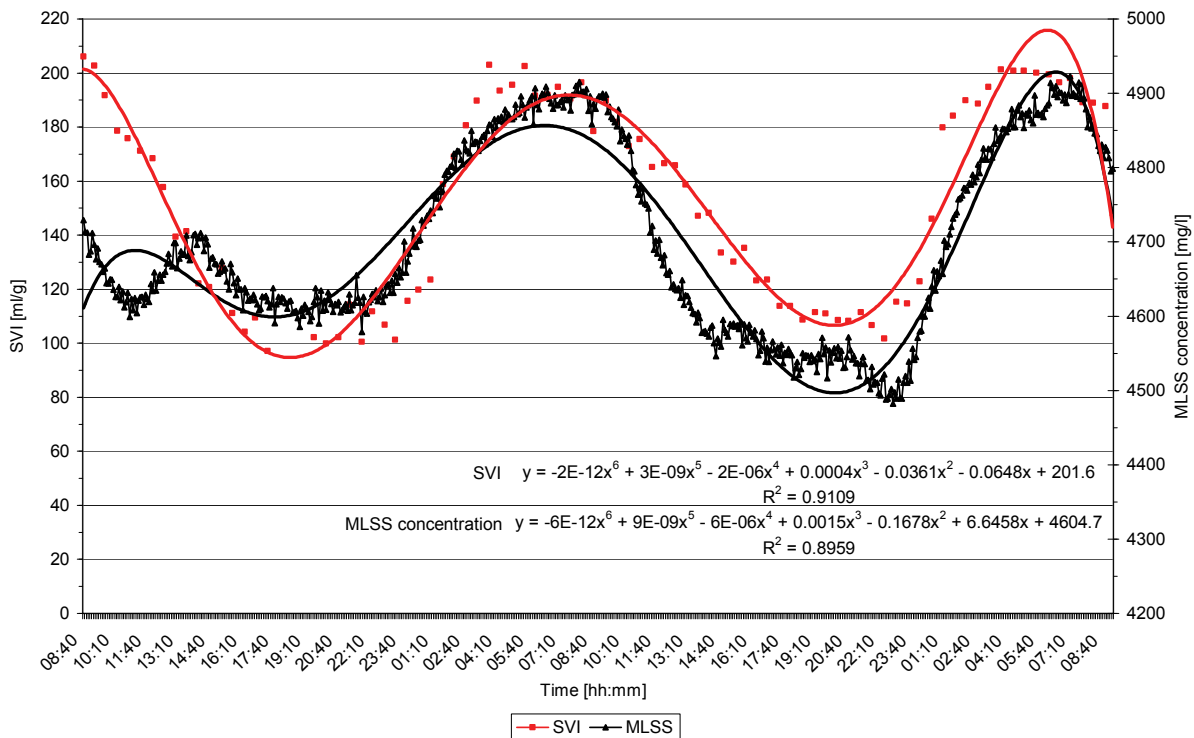
Figure 10-54 Two-day SVI and T_r profiles

Figure 10-55 Two-day SVI and MLSS concentration profiles

10.9 Appendix G: Settleability factors summary

10.9.1 Biofloc composition and structure

Table 10-19 Biofloc composition and structural properties affecting settling aspects

Parameter	Improve settling	Worsen settling	Impact description	Typical range	Reference
Density	Higher density with specific gravity (SG) of floc up to 1.06	Lower density with SG of floc up to 1.02	Heavier particles settle and compact faster	1.020	Bien <i>et al.</i> , 2005; Murthy 1998; Andreadakis, 1993;
ECP	More ECP (up to 15%) protects biofloc	Less ECP	ECP Layer decrease surface roughness, provides protective coat to flocs	N/A	Liss <i>et al.</i> , 2002; Frolund <i>et al.</i> , 1996;
Growth stage	End of log growth phase, start endogenous	Log growth or end of endogenous	Non-settleable at start, dispersed at end	N/A	Kolmentz, 2003;
Organism type	Floc former: filament ratio balance; higher organisms: swimming or crawling, such as protozoans and rotifers	Microorganism imbalance: filaments dominate over floc formers	Filaments dominance prevent settling (leads to bulking), Bridging between flocs, Floc formers suppressed, Filaments prevent downward sludge and upward water movement Higher organisms feed on dispersed flocs and free bacteria	3-5 filaments per floc-former	Martins <i>et al.</i> , 2003; Forster and Dallas-Newton, 1980; Blackbeard <i>et al.</i> , 1986; Bux and Kasan (1994a);
Polyposphosphate	Higher P increases settling velocity	N/A	Cells store polyphosphate, P increases biofloc density	N/A	De Clercq, 2003;
Porosity	Low porosity or high porosity	High porosity	Low porosity biofloc has higher density and is firm and compact and improves settling, but high porosity can also improve settling velocity of aggregate, as water can rise through settling blanket flocs Larger size more porous, and resulting lower density Low DO cause filaments and irregular shaped porous flocs	N/A	Martins <i>et al.</i> , 2003; Barbusinski and Kościelniak, 1995; Námer and Ganczarezyk, 1993;
Shape	Irregular shaped improve clarification efficiency and bridging Round, regularly shaped improves settling velocity and compression	Sphere (reduce efficiency) clarification	Shape away from sphere reduces settling velocity but improves sweep flocculation	N/A	Martins <i>et al.</i> , 2003;
Size	Medium size 200-500 µm	Too Small (no filtering effect) or too large (too porous and low density)	Balance between growth and fragmentation Settling velocity directly related to size (diameter) Anaerobic inside large flocs: break-up Surface shear increases with floc diameter	0.5 to 1000 µm	Spicer and Praisinis, 1996; Kolmentz <i>et al.</i> , 2003 ; Randall <i>et al.</i> , 1992; Wilén, 1999;
Surface charge	Higher charge	Lower charge	Negative surface charge provides negative adsorption sites to bind to positive metal cations Surface charge influences filament length (coil or straight)	-20 to -50 mV; -15 to -30 mEq/gSS	Bux and Kasan, 1994b; Liss <i>et al.</i> , 2002; Forster, 1976; Örmeci and Vesilind, 2000;
Surface solvent interaction (hydrophobicity)	Hydrophobicity larger (hydrophobic surface)	Hydrophobicity smaller (hydrophilic surface)	Cells and flocs adhere easier to hydrophobic surface	N/A	Liss <i>et al.</i> , 2002; Agridiotis <i>et al.</i> , 2006;

10.9.2 Wastewater characteristics

Table 10-20 Wastewater characteristics affecting settling aspects

Parameter	Improve settling	Worsen settling	Impact description	Reference
Alkalinity	Normal alkalinity	Low alkalinity	Low alkalinity – no buffer for nitrification loss – defoculation High alkalinity increases settling rate (>500 mg/l as CaCO ₃)	Nell, 1980; Rasmussen <i>et al.</i> , 1993
Ammonia	Low ammonia concentration < 1.5mg/l	Higher ammonia concentration	Nitrification bacteria attached to surface of compact flocs	Kruit <i>et al.</i> , 2002; Wanner <i>et al.</i> , 1988
Bacteria	Floc formers: filaments ratio balance	Filaments > floc-formers Floc formers > filaments	Filament growth leads to bulking and settling reduction	Tandoi <i>et al.</i> , 2006;
C: N: P or nutrient composition or trace elements	COD: N: P > 100:5:1 COD: NH ₄ > 5 (nitrogen limited)	COD: N: P < 100:5:1 COD: NH ₄ < 5 (carbon limited) Iron concentration low	Filaments favour N and P deficiency High C synthesis of cells and ECP production, but low C fungal growth, filaments Endogenous growth phase, filaments	Tandoi <i>et al.</i> , 2006; Nakhla and Lugowski (2003); Durmaz and Sanin (2001); Nell, 1980; Ekama <i>et al.</i> , 1997; Al-Yousfi <i>et al.</i> , 2000
Floc water	Bound floc water	Capillary water	Well formed flocs holds bound floc water, Deflocculated flocs hold capillary water, Bound water is released and decreased at low DO, Bound water is decreased at high salinity and conductivity.	Sürücü and Çetin, 1989; Forster, 1976; Sanin, 2002
FOG	No excessive quantities	Fats oils grease (FOG) from industrial sources	FOG coat flocs, and interfere with bacterial activity structure FOG covers porosity channels, and hinders water flow and entrap air bubbles	Gerardi, 2002
Metal cations	Divalent (Copper > Calcium > Magnesium selectivity to floc matrix) Divalent: Monovalent ratio > 0.5	Monovalent (sodium, potassium, ammonium)	Charge bridging and when by divalent ion, a larger surface area Biofloc is an ion exchange medium: monovalent ion exchange for divalent ion (Calcium instead of Magnesium or Sodium) Lower net negative surface charge and lower interparticle distance Increase floc size and density, stable structure, decrease porosity with divalent ions Binding ability of charged and uncharged groups on ECP	Murthy, 1998; Biggs <i>et al.</i> , 2001; Gerardi, 2002; Sürücü and Çetin, 1989; Tandoi <i>et al.</i> , 2006; Urbain <i>et al.</i> , 1993; Bruus <i>et al.</i> , 1992; Novak <i>et al.</i> , 2001;
MLVSS	Low active fraction	High active fraction	Settleability decreases at higher active fraction (or young sludge age)	Catunda and Van Haandel, 1992; Gerardi, 2002
Nitrate	Nitrate low < 1 mg/l	Nitrate > 1 to 2 mg/l (Anoxic to aerobic zone)	Filaments reduce NO ₃ to NO ₂ and will proliferate Floc formers reduce NO ₂ to N ₂ to proliferate Anoxic conditions in secondary settling tank release insoluble nitrogen gas bubbles which attach to flocs and float to surface	Hercules <i>et al.</i> , 2002; Sötemann <i>et al.</i> , 2002
Nitrogen gas	Denitrification that is completed improves compression	Denitrification not complete	Insoluble nitrogen gas adhere to bioflocs and specifically filaments, increase biofloc buoyancy	Madoni <i>et al.</i> , 2000; de Clercq, 2003

pH	Neutral pH near 7 (range 6.5 to 8.5)	Alkaline pH (pH > 8.5) or acidic pH (pH < 6.5)	No large variations in pH for stable MLSS settling, Alkaline conditions can improve settling, Filamentous fungi growth at low pH, filament proliferation when denitrification incomplete for alkalinity recovery Negative charge reduces at lower pH Deflocculation at low pH	Nell, 1980; Sürücü and Çetin, 1989; Pitman, 1975; Ekama <i>et al.</i> , 1997; Drysdale <i>et al.</i> , 2000; Gerardi, 2002;
Septicity	Increase septicity	Decreased septicity	Lower bacterial fibril charge	Gerardi, 2002
Sewage feed age	Fresh sewage (normal age) Low levels of sulphide no impact (0.5 – 2.0 mMol)	Long sewage feed age: septic sewage Acetate and sulphide: carbon sources for filaments, Sulphide from industrial sources	Filament dominance under septic conditions Deflocculation at S > 2.7 mMol	Kjellerup <i>et al.</i> , 2001; Martinez <i>et al.</i> , 2006; van Niekirk <i>et al.</i> , 1987; Jenkins <i>et al.</i> , 1984
Soaps, detergents, emulsifying agents	No excessive quantities	High concentrations industrial sources	Surface active compounds cause deflocculation of colloids, dispersed cells, small flocs, Decrease surface tension and attack perimeter of floc, Foam production and toxicity.	Kjellerup <i>et al.</i> , 2001; Gerardi, 2002
Solids content	Normal MLSS concentration: 3000 to 6000 mg/l (Extended aeration)	Low MLSS concentration High MLSS concentration	All aspects of settling related to solids content or MLSS concentration MLSS settling velocity and concentration modelled accordingly	Bhargava and Rajagopal, 1993; Catunda and Van Haandel, 1992
TDS	High TDS, specifically salinity (sodium and potassium ions) High strength: up to 0.06 M for monovalent and divalent cations	Low TDS Dilution of sample with water	High TDS: Larger floc area, elongated shape, decreased shape factor due to electrostatic and hydrophobic reactions Low TDS: Deflocculation, high turbidity Diluted sample has lower ionic strength, leads to deflocculation	Moghadam <i>et al.</i> , 2005; Gerardi, 2002; Chaignon <i>et al.</i> , 2002;
Temperature: long-term (seasonal variation)	Summer and early autumn (high temperature)	Winter and early spring (low temperature)	Filament growth at lower temperature (T _i < 20°C), <i>M. parvicella</i> growth only at T _i < 20°; Zoogloea growths more at lower T _i	Kristensen <i>et al.</i> , 1994; Mamais <i>et al.</i> , 2006; Al-Yousfi <i>et al.</i> , 2000;
Temperature: short-term (diurnal variation)	Day (high Temperature)	Night (low temperature)	Physical changes to water and biofloc	Makinia <i>et al.</i> , 2005;
Toxicants	Limited toxic concentrations	Toxic (industrial) discharges such as organic compounds e.g. phenol	Deflocculation from biofloc disintegration Large viscous clumpy bioflocs Instantaneous floc break-up	Morgan-Sagastume and Allen, 2003; Wilén, 1999; Schwartz-Mittelmann and Galil, 2000;
VFA and LCVFA	VFA and LCVFA low concentration	VFA and LCVFA concentration	Filaments use VFA to proliferate	Kruit <i>et al.</i> , 2002;
Viscosity	Low	High	Improved MLSS settling at lower viscosity Viscosity is inversely related to T _s	Hasar <i>et al.</i> , 2004;

10.9.3 Process and reactor configuration

Table 10-21 Process and reactor configuration affecting settling factors

Parameter	Improve settling	Worsen settling	Impact description on settling aspect	Reference
Aeration intensity	Low velocity surface aeration or bubble aeration	High velocity surface aeration or over - aeration causing turbulence	Physical floc break-up of shearing of sections High shear leads to irreversible floc size reductions	Ekama <i>et al.</i> , 1997; Biggs <i>et al.</i> , 2003; Parker <i>et al.</i> , 1996;
Aeration method	Fine bubble Surface aeration with draught tubes	Coarse bubble Point source surface aeration	No low DO tension in bubble aeration Turbulence for floc break-up	Van Huyssteen <i>et al.</i> , 1990; Ekama <i>et al.</i> , 1997
Aerobic reactor zone size	>55% to 60%	< 55 to 60%	Filament proliferate at low DO conditions and large anaerobic zones	Ekama <i>et al.</i> , 1997; Cooper <i>et al.</i> , 1995; Tandoi <i>et al.</i> , 2006; Pitman, 1991;
Anaerobic reactor zone size	Short anaerobic retention time Anaerobic reactor < 10%	Longer anaerobic retention time Anaerobic reactor > 10%	Deflocculation at long anaerobic time Filament growth at large anaerobic zone	Wilén, 1999; Cooper <i>et al.</i> , 1995;
Attached growth	Support material available for attached growth in reactor	No attached growth, only suspended growth in biofloc	Biofilm carrier material in reactor requires no RAS recycle Biofloc grow on inert particle or carrier such as foam or plastic discs, Maximum particle volume 40% to ensure complete mixing Reduce filamentous growth in biofilm due to anoxic zone	Wanner <i>et al.</i> , 1988, Ødegaard, 2000;
Combined sewers	Separate	Combined	Combined infiltration, high hydraulic loads due to storm water	Wilén, 1999;
Environmental	Quiescent conditions	Rainfall, wind	Rainfall dilute inflow through infiltration, hydraulic load Wind will enhance density currents and move surface scum	Ekama <i>et al.</i> , 1997; Van der Walt, 1998;
HRT in settling tank	As per design	Too short	Microorganism washout at low HRT over design capacity	Pretorius, 1987;
Inflow feed configuration	Discontinuous or intermittently fed Cyclic loading	Continuously fed	Substrate gradient favours floc-formers above filaments Larger stronger flocs with cyclic	Dangcong <i>et al.</i> , 1999; Wilén and Balmer, 1999;
Mixing intensity	Gentle mixing: for contact and suspension	Low intensity mixing: dead zones High intensity mixing: unwanted DO input	Bioflocs contact, induce flocculation Mixing reduce wall effects during settling tests in cylinders	Wilén, 1999; Grijspeerd and Verstraete, 1997; Berkay, 1998;
Prefermentation	No prefermentation, (or Prefermentation depending on VFA)	Prefermented settled sewage reactor feed	<i>M. parvifolia</i> store LCVFA under anaerobic conditions But 7.5 mg/t VFA per 1 mg/l P can minimise anaerobic zone size and improve settling	Mamais <i>et al.</i> , 2006; Cooper <i>et al.</i> , 1995;

Primary settling	Primary settling No primary settling	No primary settling Primary settling	Remove some RBCOD and VFA which stimulates growth of filaments such as <i>Microthrix parvicella</i> Nutrient rations change	Mamais <i>et al.</i> , 2006; Tandoi <i>et al.</i> , 2006;
Reactor configuration	Plug flow or SBR or oxidation ditch Declining growth phase	Completely mixed reactor Log growth phase	Spatial substrate gradient in plug flow favours floc-formers Temporal substrate gradient SBR favours floc-formers Completely mixed reactor has backmixing and mobile organisms proliferate	Droste, 1997; Janczukowicz <i>et al.</i> , 2001; Azimi and Horan, 1991; van Niekirk <i>et al.</i> , 1987; White, 1976; Pitman, 1975; Kruit <i>et al.</i> , 2002
Reactor surface flow	Free surface flowing Reactor zone surface organism removal Mechanical foam removal	Internal recirculation of foam/scum microorganisms Trapped foam	Remove scum/foam organisms out of system Surface layers with foam or floating matter retention age > sludge age of bulk activated sludge : due to trapping and recirculation, cause foam proliferation Surface aerators have surface pump-back action to return foam upstream	Tandoi <i>et al.</i> , 2006; Blackbeard <i>et al.</i> , 1986; Madoni <i>et al.</i> , 2000; Pitman, 1991; Pitman, 1996
Selectors	Sectionalised selector short HRT : 5 minutes in 3 sections Selectors loading: 100 mg COD. g MLSS .h ⁻¹	HRT not suitable Too large or too small selector Selector loading too low or high	High VFA uptake by floc-formers, substrate gradient favours floc-formers Floc-formers are fast-growers, filaments are slow-growers Too small selector: substrate into reactor, Too large selector: removal of substrate too large	Tandoi <i>et al.</i> , 2006; Kruit <i>et al.</i> , 2002; Cenens <i>et al.</i> , 2000; Van Niekirk <i>et al.</i> , 1987;
Settling tank design	Deep tank (>5m): sweep flocculation Large centre well: reflocculation Sloped floor: fast sludge removal Baffles: surface scum removal	Shallow tank (< 5m depth) Small centre well Flat floor: slow sludge removal No baffles	sweep flocculation reflocculation denitrification surface foam	Parker <i>et al.</i> , 1996;
Settling tanks configuration	Tanks in series	Tanks in parallel	Micro-organism selection occurring in tanks by removing filaments in 1 st tank	Kim <i>et al.</i> , 1998;
Simultaneous precipitation	Precipitation	No precipitation	C and P nutrient deficiencies and filamentous growth from precipitation Stabilisation time required to restore settling	Ødegaard, 2000; Eriesson and Erkkson, 1988; Janssen <i>et al.</i> , 2002;
Turbulence: hydraulic jump or pumping	Low turbulence and gentle transfer (Can enhance settling if DO is increased)	High turbulence, high pump impeller velocity	Biofloc deflocculate during shear, Break-up more during aggregation	Wilén, 1999;
Ultrasound	Sonification time low (about 180s) at 22kHz and 16 µm,	Sonification time high (about 360s) at 22kHz and 16 µm	Ultrasonic cavitation bubbles can destroy filaments with Increased settling velocity, lower SVI, lower hydration, but at high intensity shear cause cell destruction, dispersed floc, and irreversible deflocculation	Bieñ <i>et al.</i> 2005; Wünsch <i>et al.</i> , 2002;

10.9.4 Operational factors

Table 10-22 Operational factors affecting settling factors

Parameter	Improve settling	Worsen settling aspect	Impact description on settling aspect	Reference
Additives: Synthetic polymers, inorganic coagulants, anti-foaming agents, weighing agents	Structure change to compact dense flocs; Hydrophobicity increase	Overdosing of these additives, and introduction of new constituents	Fast changes within 30 to 45 min., ideal as short-term standby or emergency use but temporary measure only (e.g. 4 hr) with relative high cost of chemicals Ballasting effect, floc restructuring, thin biofilm Initial lag period, SVI, ISV, SV ₃₀ improvement	Wilén, 1999; Agridiotis <i>et al.</i> , 2006; Patoczka <i>et al.</i> , 1998; Vanderhasselt and Verstraete, 1999; Vanderhasselt <i>et al.</i> (1999a);
Anaerobic time	Shorter anaerobic Anaerobic reactor < 10%	Longer anaerobic time	Deflocculation at long anaerobic time Filament growth at large anaerobic zone	Wilén, 1999; Cooper <i>et al.</i> , 1995;
Anoxic reactor outlet nitrite	Low NO ₂ concentration	High NO ₂ concentration (>1 to 2 mg NO ₂ /l)	Bulking sludge due to high nitrite concentration Control the a- recycle according to denitrification potential	Lilley <i>et al.</i> , 1997;
Bactericide	Chlorine, hydrogen peroxide, ozone Lower SVI and effluent suspended solids, higher settling velocity	Overdosing of bactericide: effluent SS increase, Floc formers can be affected Introduction of new constituents	Non-specific bulking control by filament killing Temporary solution High cost 2 to 8 mg Cl ₂ /(gMLSS.d) for 19 days reduces DSVI from 230 to 48 ml/g	Seka <i>et al.</i> , 2001; Van Leeuwen and Pretorius, 1988; Wentzel <i>et al.</i> , 1988;
DO concentration	DO = 2 mg/l over 24 hr in whole aerobic reactor (ideally), or minimum 1 mg/l over 24 hours in all sections of aerobic reactor	Over aeration (DO>3 mg/l) Under aeration (DO <1 mg/l) in zones or certain times, Oxygen limitation (DO< 0.5 mg/l) Intermittent or alternating aeration	Increase DO: mechanical or point source aerators turbulence will shear sensitive flocs, Filament dominance, Deflocculation, irregular weak flocs, low ECP production; low adsorption colloids; porous flocs: anaerobic period determines deflocculation, Diffusional limitation inside flocs at a low DO, DO according to organic loading [2 mg/l DO for 0.5 kg COD/kg MLVSS/d], Higher DO (>2 mg/l) create large stable compact flocs, High DO and over-aeration cause foams; High DO in a-recycle to anoxic zone reduces BNR efficiency.	Jones and Franklin, 1985; Kabouris and Georgakakos, 1990; Kjellerup <i>et al.</i> , 2001; Martins <i>et al.</i> , 2003; Tandoi <i>et al.</i> , 2006; Wilén, 1999; Wilén and Balmér, 1999; Pitman, 1991;
Organic loading	Organic loading high	Organic loading low Organic loading overload (long-term)	Filament dominance at low substrate, larger surface: volume Floc formers have higher substrate utilisation rates Floc formers cannot absorb too high substrate loading: break up Diffusional resistance inside flocs for high loading: break up Size of flocs increase with increased loading	Jones and Franklin, 1985; Tandoi <i>et al.</i> , 2006; Barbusinski and Kościelniak, 1995; Pitman, 1975;
Plant stability	Start-up	Steady state	Start up unstable, microorganisms need period of a few sludge ages to acclimatise Bioflocs flocculate poorly in log growth phase when compared to declining growth phase	Kolmetz <i>et al.</i> , 2003;
RAS recycle rates	High RAS recycle (>1)	Low RAS recycle (<1)	High contact for flocculation; Prevent clarifier denitrification	Cloete and Muyima, 1997;
Sludge age (SRT)	SRT high (>15 days for EPBNR)	SRT low (< 10 to 15 days EPBNR), or very high	High sludge age (15 to 20 days): Biofloc more stable, compact, floc surface more hydrophobic, less negatively charged, less hydrated, large ECP layer gives smoother surface and protective coat; Higher life forms scavenge effluent dispersed fragments; High sludge age: Filament dominance at very high sludge age; Low sludge age: weak buoyant floc shear easily no structure.	Liss <i>et al.</i> , 2002; Liao <i>et al.</i> , 2001; Akca <i>et al.</i> , 1993; Kaewpittat and Grady, 2002; Nakhla and Lugowski, 2003; Gerardi, 2002;

10.9.5 Settleability failure identification

Table 10-23 Settleability failure identification guidelines
(adapted from Jenkins *et al.*, 1986)

Name of problem	Nature of problem or alternative names	Characterization of problem	Reasons for problem
Dispersed floc	Flocs do not aggregate, small clumps (10 to 20 μm) or single cells (Dispersed growth, straggler flocs)	Turbid effluent No or very low zone settling velocity Low sludge age from loss of sludge in settling tank	Low amount of ECP High organic loading Start-up of plant or low sludge age Toxicity event
Filamentous floc	Strong, large flocs Filaments extend from flocs into bulk solution, interfloc bridging Interfere with settling and compression Filaments cause foaming (<i>Norcardia</i> or <i>Microthrix parvicella</i>) (filamentous bulking)	Clear effluent Poor thickening and low RAS concentration Increased sludge blanket High SVI and high SV ₃₀	Nutrient deficiency High organic loading or shock load Low DO concentration Low pH Septicity or high sulphide levels
Floating flocs	Bio surfactants or surface active agents from foam forming filaments Floating foams from hydrophobic filaments, accumulate on surfaces Bacteria causing foams dominate	Foams visible in aerator and settling tank, aesthetic Carryover cause high nutrient content in effluent Low density billowy foam or heavy dense foam	Internal circulation of material and not removed from system Low temperature or seasonal changes Low sludge age Low DO concentration High organic shock load Industrial surface active agents
Non-filamentous floc	Sludge flocs become more hydrated and reduce density Bound water in sludge flocs due to hydrophilic biopolymers Exocellular slime or jelly-like characteristics of sludge solids (viscous bulking, hydrous zoogeal bulking, non-filamentous bulking)	Low settling velocity Low compression and low RAS concentration Increased sludge blanket High SVI	Low sludge age Nutrient deficiency High organic loading or shock load Low DO concentration
Pin floc	Compact dense flocs settle rapidly, leaving lighter flocs in suspension Weak, small flocs Break up of large flocs (Pin-point floc, unsettleable floc)	Cloudy turbid effluent with fine particles High zone settling velocity Few filaments Low SVI	High DO concentration High turbulence from aerators or hydraulic jumps High shear High sludge age Low organic loading Absence of filaments
Rising flocs	Gas entrainment or gas release gives buoyancy to flocs Bubble aeration MLSS supersaturated with air Denitrification of nitrate in blanket with insoluble nitrogen gas release Long retention in settling tank make sludge anaerobic with gas release	Settle rapidly and compact well Flocs or clumps of flocs rise rapidly to surface, within 30 minutes to interfere with SVI test	Low RAS flow rate High sludge blanket or tank floor accumulation Reactor denitrification incomplete

10.9.6 Settleability impacts due to filamentous micro-organism dominance

Table 10-24 *Microthrix parvicella* dominance and settling effects in a NDBEPR process
(adapted from Tandoi *et al.*, 2006)

Parameter	<i>Microthrix parvicella</i> compared to floc-formers	<i>Microthrix parvicella</i> dominance impact on settling
Biocides	20 to 200 kgCl ₂ /kgSS effective for <i>Microthrix parvicella</i> ; 2 kg Cl ₂ /kg SS normal dosing for other filaments	Hydrophobic cell wall prevents penetration to reduce <i>Microthrix parvicella</i> dominance
Cell wall	<i>Microthrix parvicella</i> hydrophobic	Supports formation of stable foams, Scum and bulking in same reactor attributed to <i>Microthrix parvicella</i>
Electron acceptors	<i>Microthrix parvicella</i> uses DO, NO ₃ , NO ₂	All reactor zone grower (anaerobic, anoxic, aerobic) and related settleability deterioration
Maintenance energy	<i>Microthrix parvicella</i> has lower requirements, and can adapt and withstand environmental stress	Advantage under starvation conditions (low substrate loading such as C, N, O) leads to proliferation and related settleability deterioration
Oxygen affinity	<i>Microthrix parvicella</i> has high affinity	Advantage during micro-aerobic conditions During low DO concentration or plant overload More prevalent in surface aeration with low DO concentration sections
pH	Stimulated <i>Microthrix parvicella</i> growth alkaline pH (>8)	NDBEPR recovers alkalinity for resulting higher pH, and related settleability deterioration
Slowly biodegradable substrate	<i>Microthrix parvicella</i> grows well with SBCOD, and also a specialised lipid consumer	Kinetic selectors are not effective to reduce <i>Microthrix parvicella</i> dominance
Sludge age	Enhanced <i>Microthrix parvicella</i> growth at long sludge ages (>10 days)	NDBEPR process sludge age above 15 days, and related settleability deterioration
Strains	Numerous	Contradictory information; Difficult to isolate and cultivate
Symptoms	Varied indications makes identification difficult	Bulking and scum formation in same reactor
Temperature	Enhanced <i>Microthrix parvicella</i> growth at 12- 15°C (winter temperatures) <i>Microthrix parvicella</i> growth stops above 20°C (summer temperatures)	Seasonal or periodic dominance, and related long-term changes in settleability
Volatile fatty acids	Enhanced <i>Microthrix parvicella</i> growth with LCVFA in anaerobic reactor zones	LCVFA enriched settled sewage feed from prefermenters; <i>Microthrix parvicella</i> proliferation from anaerobic reactor in NDBEPR process and related settleability deterioration

10.10 Appendix H: Summary of regression model variable results

Table 10-25 Regression variable results

Parameter	Residual sum of squares	(absolute)	Standard error of estimate	Proportion of variance explained [%]	variable	Value	Standard error	t-ratio	p value	95% confidence interval		
										95% (+/-)	Lower limit	Upper limit
SV1	33051.9430		20.0767	71.0372	a	872.4200	159.1041	5.48	0	316.5058	555.9142	1188.9258
					b	-4624176.0614	445895.8905	-10.37	0	887020.6949	-5511196.7563	-3737155.3665
					c	4823.4020	1611.5791	2.99	0.0037	3205.9143	1617.4878	8029.3163
t_umax	2419.6831		5.4322	70.2409	a	239.5624	43.0489	5.56	0	85.6372	153.9252	325.1996
					b	-1290679.9382	120646.3577	-10.70	0	240001.7994	-1530681.7375	-1050678.1388
					c	939.9347	436.0461	2.16	0.034	867.4264	72.5082	1807.3611
u_max	7.7978		0.3084	58.9421	a	-9.30	2.44	-3.81	0.0003	4.86	-14.16	-4.44
					b	57454.30	6848.89	8.39	0	13624.50	43829.76	71078.76
					c	-39.8603	24.75	-1.61	0.11	49.24	-89.10	9.38
u_ave	0.3879		0.0688	75.5813	a	-2.89	0.55	-5.31	0	1.08	-3.98	-1.81
					b	18433.81	1527.63	12.07	0	3038.92	15394.90	21472.74
					c	-15.18	5.52	-2.74	0.007	10.98	-26.16	-4.20
h	94532.14		33.9535	76.0927	a	1793.96	269.07	6.67	0	535.27	1258.69	2329.23
					b	-9200670.30	754092.67	-12.20	0	1500116.54	-10700786.85	-7700553.76
					c	7744.02	2725.48	2.84	0.006	5421.80	2322.23	13165.82
u1	2.4349		0.1723	32.0137	a	-1.1851	1.3656	-0.86	0.388	2.7166	-3.9018	1.5315
					b	14418.7348	3827.1866	3.77	0.0003	7613.4223	6805.31	22032.1571
					c	-31.9946	13.8324	-2.31	0.023	27.5168	-59.5115	-4.4778
U2	4.2432		0.2275	59.0884	a	-2.6708	1.8027	-1.4815	0.1423	3.5861	-6.2570	0.9153
					b	33145.3653	5052.1882	6.5606	0	10050.3181	23095.0472	43195.6834
					c	-74.7660	18.2598	-4.0946	0.0001	36.3244	-111.0903	-38.4416
u3	1.4572		0.1333	62.3507	a	-3.6732	1.0564	-3.4770	0.00081	2.1016	-5.7748	-1.5717
					b	25152.0675	2960.7089	8.4953	0	5889.7381	19262.3293	1041.8057
					c	-26.7192	10.7007	-2.4969	0.0145	21.2870	-48.0062	-5.4322
u4	0.6809		0.0911	59.5538	a	-4.1828	0.7222	-5.7921	0	1.4366	-5.6194	-2.7462
					b	19564.9547	2023.8724	9.6671	0	4026.09	15538.8655	23591.0440
					c	3.4218	7.3148	0.4678	0.6411	14.5513	-11.1295	17.9731
u5	0.5620		0.0838	33.6828	a	-3.3897	0.6561	-5.1666	0	1.3051	-4.6948	-2.0846
					b	11822.7573	1838.6975	6.4300	0	3657.7208	8165.0364	15480.4781
					c	18.7500	6.6455	2.8215	0.006	13.2199	5.5301	31.9700
u6	0.3475		0.0651	29.5519	a	-2.6835	0.5159	-5.2019	0	1.0262	-3.7097	-1.6573
					b	8411.5793	1445.7612	5.8181	0	2876.0528	5535.5265	11287.6321
					c	18.8984	5.2253	3.6167	0.00051	10.3948	8.5037	29.2932